Interactions Between the Auditory and Vibrotactile Senses: A Study of Perceptual Effects

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ABSTRACT

This project is an experimental study of perceptual interactions between auditory and tactile stimuli. These experiments present vibrotactile stimuli to the fingertip and auditory tones diotically in broadband noise. Our hypothesis states that if the auditory and tactile systems integrate, the performance of the two sensory stimuli presented simultaneously will be different from the performance of the individual sensory stimuli. The research consists of work in two major areas: (1) Studies of the detection of auditory and tactile sinusoidal stimuli at levels near the threshold of perception (masked thresholds for auditory stimuli and absolute thresholds for tactile stimuli); and (2) Studies of loudness matching employing various combinations of auditory and tactile stimuli presented at supra-threshold levels. Results were compared to three models of auditory-tactile integration.

The objective detection studies explore the effects of three major variables on perceptual integration: (a) the starting phase of the auditory relative to the tactile stimulus; (b) the temporal synchrony of stimulation within each of the two modalities; and (c) the frequency of stimulation within each modality. Detection performance for combined auditory-tactile (A+T) presentations was measured using stimulus levels that yielded 63%-77%-correct unimodal performance in a 2-Interval, 2-Alternative Forced-Choice procedure.

Results for combined vibrotactile and auditory detection indicated: (1) For synchronous presentation of 500-msec, 250 Hz sinusoidal stimuli, percent-correct scores in the combined A+T conditions were significantly higher than scores within each single

modality; (2) Scores in the A+T conditions were not affected by the relative phase of the 250 Hz auditory and tactile stimuli; (3) For asynchronous presentation of auditory and tactile 250 Hz stimuli, scores on the A+T conditions improved only when the tactile stimulus preceded the auditory stimulus (and not *vice versa*); and (4) The highest rates of detection in the combined-modality stimulus were obtained when stimulating frequencies in the two modalities were equal or closely spaced (and within the Pacinian range).

The lack of phase effect suggests that integration operates on the envelopes rather than on temporal fine structure. The effects of asynchronous presentation imply a shorter time constant in the auditory compared to the tactile modality and are consistent with time constants deduced from single-modality masking experiments. The effects of frequency depend both on absolute frequency and on relative frequency of stimulation within each modality. In general, we found that an additive sensitivity model best explained detection performance when tones were presented synchronously and of the same frequency.

In the second area of research, loudness matching was employed in a subjective study of the effects of frequency on auditory-tactile integration for stimuli presented at supra-threshold levels. These experiments, which were derived from previous auditory studies demonstrating the dependence of loudness on critical-band spacing of tonal signals, employed various combinations of auditory and tactile stimuli that were presented at equally loud levels in isolation. Loudness matches were obtained for auditory-only (A+A) and auditory-tactile (A+T) stimuli that were both close as well as farther apart in frequency. The results show that the matched loudness of an auditory pure tone is greater when the frequencies of combined stimuli (both A+A and A+T) are farther apart in frequency than when they are close in frequency. These results are consistent with the results found in the previous experiment exploring the frequency relationships at near-threshold levels, as well as with results in the psychoacoustic literature, and suggest that the auditory and tactile systems are interacting in a frequency-specific manner similar to the interactions of purely auditory stimuli.

The research conducted here demonstrates objective and subjective perceptual effects that support the mounting anatomical and physiological evidence for interactions between the auditory and tactual sensory systems.

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Chapter 1. Introduction and Background

Based on evidence for auditory and tactile interaction at the neurophysiological level, this research presented in this thesis investigated potential perceptual integration between these two sensory modalities in a systematic and objective manner. In this thesis, *interaction* is defined as an influence of one sense over another, or in the case of the neurophysiological studies, one sensory area responding to stimuli from a different sensory system. *Integration*, on the other hand, is defined as being a measurable and significant increase or decrease in response from stimuli from more than one sensory system over the response from either sensory system presented in isolation. Additionally, a classical definition of multisensory integration states that the response from the combined-sense stimuli is greater than the sum of the responses from the individual senses (Stein and Meredith, 1993). Specifically, this document presents research that measured integration between stimuli presented through audition and touch in a series of perceptual experiments to examine auditory-tactile integration in the following areas: 1) Perceptual integration between auditory and tactile stimuli for detection of signals near threshold in both sensory modalities. 2) Perceptual integration between auditory and tactile stimuli for supra-threshold signals in both modalities that are matched for loudness.

This thesis research has significance for increasing our knowledge of how the auditory and somatosensory systems interact with one another perceptually by utilizing objective paradigms to experimentally measure response values for single- and combined-sense stimuli. To date there have been no objective psychophysical studies that have measured auditory-tactile integration in detection as extensively and systematically as the current thesis. Additionally, the recent physiological studies have examined only gross audio-tactile interactions (i.e., using median nerve stimulation, and various supra-threshold auditory stimuli). The experiments detailed here were designed to explore the effects of various stimulus parameters on audio-tactile integration, thereby possibly shedding light on how these two sensory systems interact with one another perceptually.

1.2 Background

Previous research in the area of auditory and tactile interaction is reviewed below in three broad categories, namely: anatomical, physiological and perceptual studies.

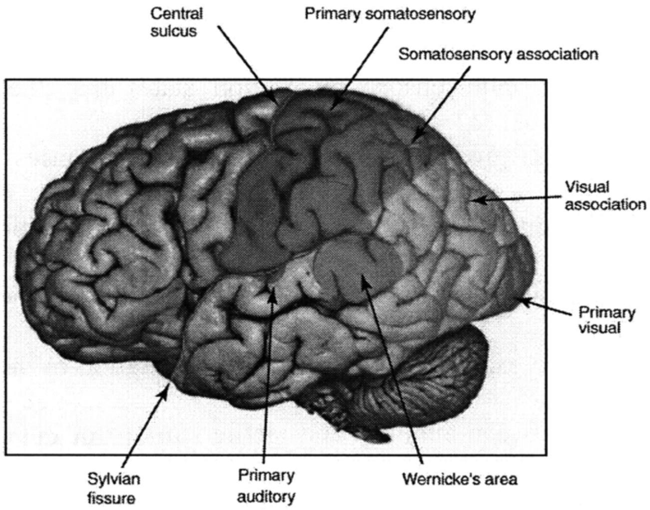

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Figure 1: Schematic of the different sensory regions in the cortex of a mammal. The auditory cortex is inside the fold ventral to the Sylvian fissure. Wernicke's area is highlighted here because it is believed to be an area important in language processing in humans. From Squire et al. (2002).

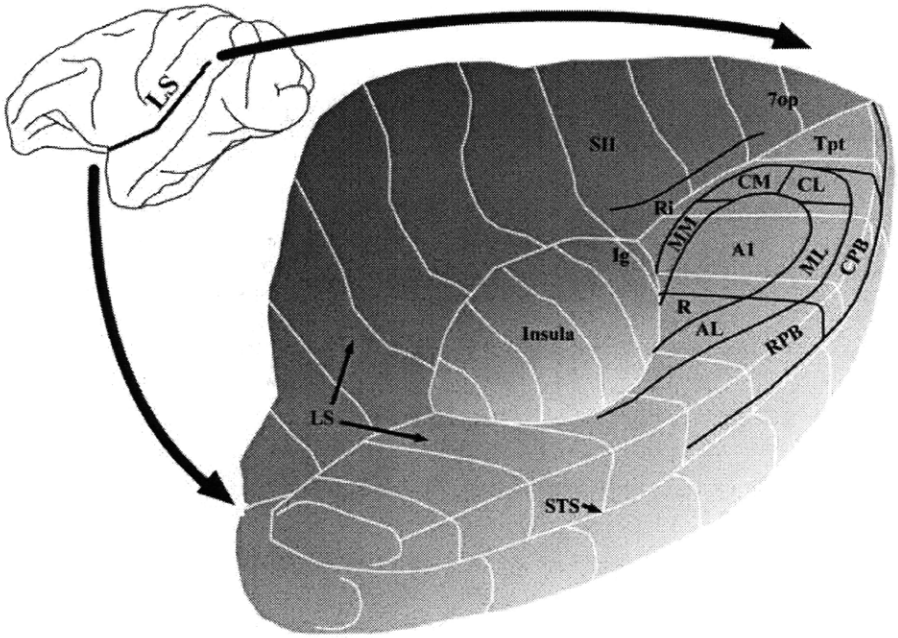

Figure 2: Drawing of anatomical locations that are inferior to the lateral sulcus, an area which is hidden from view in Figure 1. Auditory cortex (A1, CM, CL, MM, ML, R, AL regions) and somatosensory cortex (SII) and multisensory areas (Ri, Tpt) between the two cortices in macaque monkey are labeled. From Smiley et al (2007).

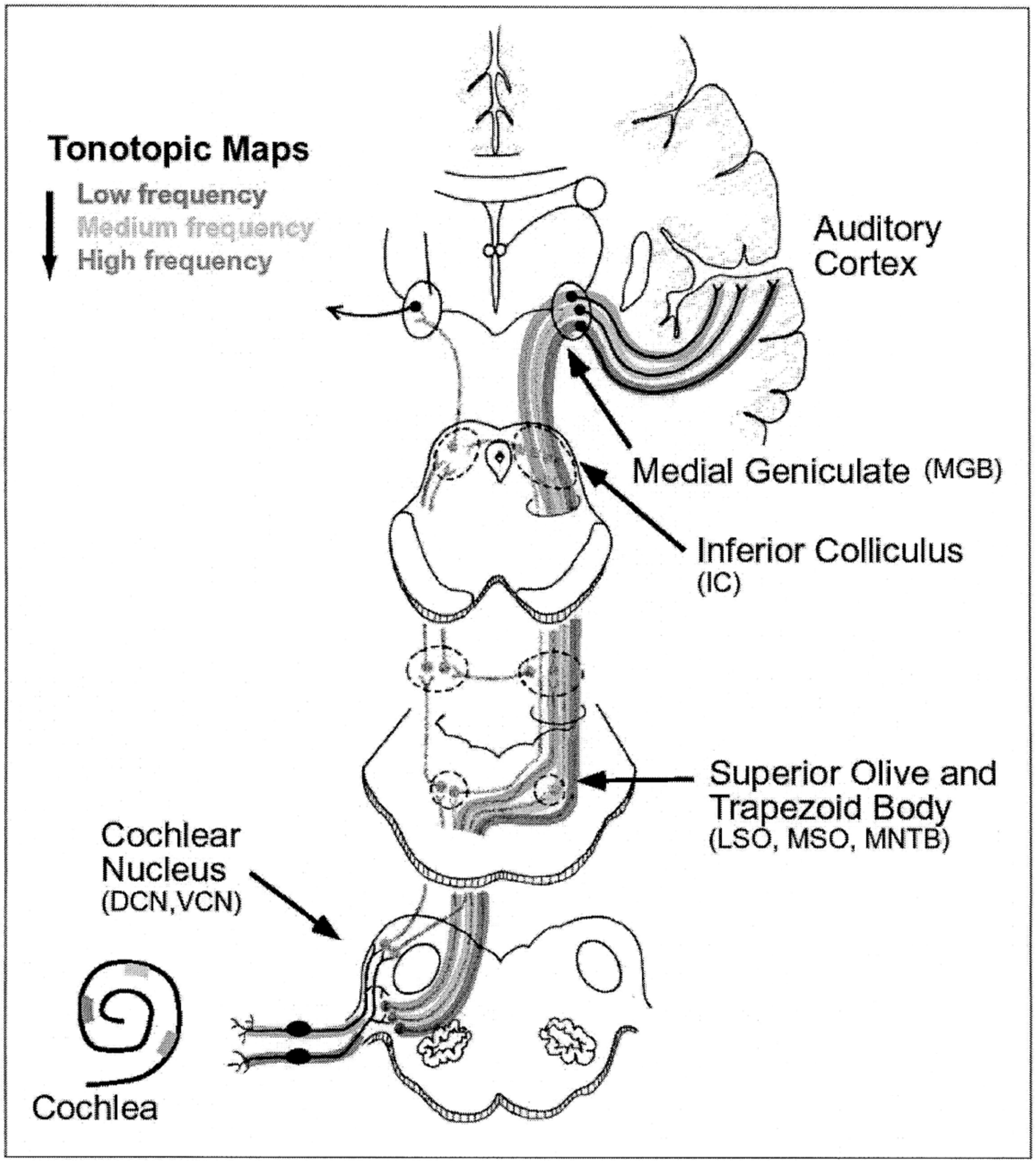

Figure 3: The ascending auditory pathway, from the cochlea (peripheral nervous system) to the cortex (central nervous system) for a mammal. The cochlea is part of the peripheral nervous system, and the central auditory system consists of the cochlear nucleus (CN), the superior olive (SO) trapezoid body (TB), inferior colliculus (IC; all a part of the auditory brainstem); the medial geniculate body (MGB, which is part of the thalamus); and the auditory cortex (AC). (From Lecture notes Neural Coding (HST.723), J. Iverson.

1.3 Anatomy

Recent anatomical studies indicate that areas of the central nervous system that have traditionally been thought to receive primarily auditory inputs may also receive inputs from the somatosensory system. Figure 1 shows a schematic drawing of the different sensory cortices in a mammalian brain. The somatosensory cortex is just posterior to the central sulcus and the auditory cortex is inferior to the Sylvian fissure, and is therefore not fully shown in this diagram. Figure 2 shows a schematic drawing of the macaque monkey brain pictured as though the brain areas above the Sylvian fissure were absent and therefore gives a more detailed view of the auditory cortex. It can be seen that the auditory and somatosensory cortices are anatomically near to one another in this animal. Figure 3 is a schematic of the ascending auditory pathway in a mammal, showing how the frequency maps originating in the cochlea (in the periphery) are preserved as they progress to the brainstem (cochlear nucleus, olivary complex and inferior colliculus), the thalamus (the medial geniculate body is the auditory center of the thalamus), terminating in the auditory cortex. In the following anatomical discussion, references will be made to areas of the auditory brainstem, thalamus and cortex that pertain to sites of auditory-tactile interaction.

Shore and Zhou (2006) review experiments that they and others have performed which show the anatomy and physiology of trigeminal nerve inputs to the cochlear nucleus and inferior colliculus of the guinea pig (the trigeminal nerve is responsible for enervating the upper and lower jaw as well as the upper facial area; see Figure 3 for anatomical locations of cochlear nucleus (DCN and VCN) and inferior colliculus (IC)).

In much of their work, the authors injected retrograde tracers into the DCN and VCN (auditory) and trigeminal ganglion (somatosensory). Their results showed anatomical pathways connecting the DCN and VCN with the trigeminal ganglion. The authors postulate that because the trigeminal ganglion is partly responsible for enervating the mouth and face, the neural pathways connecting the somatosensory system to the auditory brainstem are to attenuate the internal perception of self-made sounds (such as breathing, eating, vocalizing, etc).

In another study, Hackett et al. (2007) used retrograde tracers to measure thalamic inputs into non-primary areas of the auditory cortex. In the auditory cortex (AC) they injected tracers into the caudo-medial (CM) area, a site in secondary auditory cortex implicated in many recent studies showing auditory and tactile interaction, the caudo-lateral (CL) area, and the retro insular (Ri) area (see Figure 2 for anatomical locations). They then measured into which site these tracers terminated. The authors found that different areas of the thalamus (medial geniculate body, see Figure 1 for anatomical locations) projected to different areas of the auditory cortex. For example, in the macaque monkey, the ventral division of the auditory thalamus (i.e., medial geniculate complex, MGV, which is frequency tuned) projects mostly to primary auditory cortex, while the dorsal division of the MGB (historically a multi-sensory site receiving somatosensory inputs) and the medial division (also multisensory) project to areas CM, CL and Ri of the auditory cortex. These results show that multisensory areas in the MGB project to the areas of the AC that have been implicated in recent neurophysiological auditory-somatosensory interaction studies, thus showing that these multisensory interactions in the AC are in part due to inputs from the ascending pathway and not always from interactions in the association cortex (as previously believed).

Intra-cortical connections from somatosensory cortex to auditory cortex have also been shown using retrograde tracers. For example, Cappe and Barone (2005) injected retrograde tracers into the core area of the AC, the somatosensory cortex (areas 1/3b) and the visual cortex (V2 and MT) of the marmoset monkey. The authors found connections originating in secondary somatosensory cortex and projecting to primary auditory cortex. While they did not report finding any projections from the auditory to the somatosensory cortex, they did show polymodal projections in two specific cortical areas. For example, the area adjacent to the posterior tip of the lateral sulcus (LaS, see Figure 2 for anatomical location) and an area in the frontal lobe which is responsible for sending projections to all three modalities (audition, somatosensation and vision).

Smiley et al. (2007) used retrograde tracers to show connections between the "belt" area of the auditory cortex (which is just secondary to primary auditory cortex) and somatosensory cortical areas of the macaque monkey (see Figure 2). They injected tracers into areas CM and CL of the auditory cortex, areas which were shown by previous physiological work to exhibit strong auditory-somatosensory interactions. They also injected retrograde tracers into area Ri, which is an area that lies between the auditory and somatosensory cortices and is primarily a somatosensory site. Their results showed that the areas in the auditory-belt cortical region received inputs from the secondary somatosensory cortex, granular insular cortex (Ig), Ri, and inputs from the multisensory areas in the parietal cortex such as the temporal parietal area (Tpt), the temporal parietal occipital area (TPO) and parietal area 7a (7a).

The anatomical studies discussed here show that the areas of central nervous system that were thought to be primarily auditory also receive inputs from somatosensory areas. The complementary connection paradigm (i.e., auditory projecting to somatosensory) has not been shown anatomically as of this date.

1.4 Physiology

Recent physiological studies show that the auditory cortex is activated both by somatosensory input alone and by combined auditory and tactile stimuli. The following discussion will review literature that pertains to the discussion of auditory-tactile *interaction* and *integration* separately, first looking at auditory cortex neurons responding to tactile stimuli and then looking at the response patterns when both auditory and tactile stimuli are delivered together.

Integration is defined here as a response to the combined auditory and somatosensory stimulus that is greater than the sum of the individual sensory responses. Facilitation is defined here as being a response that has an amplitude which is greater than baseline, while inhibition is defined here as being a response that is less than baseline, where baseline is either a single or a combined sense stimulus.

In many of the studies discussed below, the somatosensory input comes from electrical stimulation of the median nerve. Figure 4 shows a schematic drawing of the median nerve in the forearm of a human. The median nerve enervates the palmar side of the thumb (thenar eminence), the index and middle fingers and half of the ring finger.

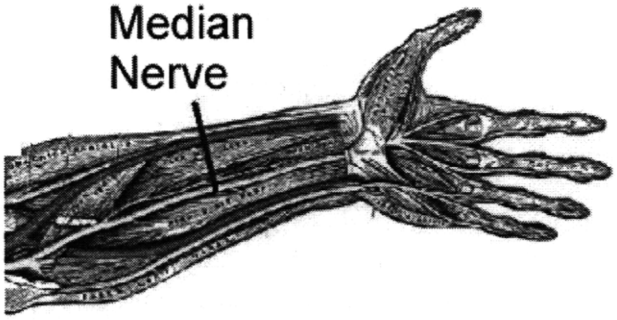

Figure 4: Schematic of the path of the median nerve through the human forearm and ending in the hand. The median nerve enervates the thumb pad (thenar eminence), the index and middle fingers, and half of the ring finger. Adapted from Gray et al (1995).

1.4.1 Interaction

Schroeder et al. (2001) were the first investigators to examine the auditory cortex of macaque monkeys for somatosensory responses and showed that an area of the auditory cortex caudal-medial (CM) to the primary belt area responds robustly to somatosensory stimulation in addition to auditory stimulation. However, they did not look at responses to combined auditory–somatosensory stimulation. The authors used current source density (CSD) as a measure of synaptic activity and multi-unit activity (MUA) as a measure of action potential activity. For tactile inputs, the authors used 100 μsecond electrical stimulation of the median nerve on the arm contralateral to the auditory cortex they were recording. They used auditory clicks, pure tones, band-pass noise and combinations of these stimuli presented binaurally over headphones in order to localize the auditory cortex. The authors showed that primary auditory cortex responded robustly to auditory stimuli and not at all to somatosensory stimulation. In the CM region, however, the authors measured CSD and MUA responses to each of the auditory and somatosensory stimuli. The response patterns from the auditory and somatosensory stimuli were largely excitatory and had large initial onset peaks that were almost equal in onset time. While the auditory CSD response diminished over 200 ms, the somatosensory CSD response maintained a plateau for approximately 200 ms before declining to baseline. The authors felt that given the short onset latencies and response patterns, the somatosensory inputs to area CM of auditory cortex must be originating from either thalamic or primary sensory cortices rather than association cortices (which would have resulted in a longer onset latency).

In a follow-up study, Fu et al. (2003) investigated in more detail the nature of the somatosensory responses in the area CM in the macaque monkey. The authors used 100 ms pure tones and "complex noises" for auditory stimuli and the following tactile stimuli: Cutaneous stimulation, deep pressure, joint manipulation, vibration to hands, and air puffs to the whole body surface (except for those parts exposed due to surgery). The authors used multi-neuron cluster recordings to measure neuronal responses in primary auditory cortex as well as area CM. They found that the neurons in area CM responded to both the auditory and tactile inputs, but that primary auditory cortex responded only to auditory inputs. They also concluded that based on the response pattern and timing the neurons in AC were receiving feed forward inputs (i.e., thalamic or intra-cortical) as opposed to feedback input (i.e., from other association cortices). These data corroborated the findings of Schroeder et al (2001).

In a complementary study, Foxe et al. (2002) used fMRI to show that areas of the human auditory cortex also respond to somatosensory stimuli in audiometrically normal human subjects. The authors used 962 ms of auditory broad band noise presented supra-threshold and binaurally over headphones. The tactile input consisted of coarse-grain sandpaper which was rolled against the tips of the index and middle fingers of the subjects' right hand in such a way as to generate a strong tactile percept. The authors imaged subjects in the conditions of auditory alone, tactile alone, and simultaneous auditory and tactile stimulation. They then contrasted the two single-sense presentations against the combined response focusing only on the area in the left hemisphere that showed overlapping activation between the two single-sense stimulus presentations. The overlapped area was located in the temporal lobe, posterior to the primary auditory cortex and the authors found interactions that showed a response which was greater in the simultaneous condition compared with the summation of the two single-sense conditions, a classical definition of multisensory integration. The authors concluded that this area was the human homologue of the macaque monkey area CM found in previous studies showing strong auditory-somatosensory interactions.

Caetano and Jousmaki (2005) used whole-scalp MEG, a tool with temporal resolution on the order of hundreds of milliseconds, to study the effects of somatosensory stimuli on the auditory cortex in humans. The vibrotactile stimulus consisted of a 500 ms 200 Hz signal delivered to the right hand (all four fingers and thumb) via a silicone tube at 15-22 dB above threshold (SL). The authors reported that in all 11 subjects the contralateral temporal-parietal area showed a significant response to the vibrotactile stimuli. Eight of the subjects also showed a transient response in the ipsilateral temporal-parietal area. Because MEG has good temporal acuity but poor spatial resolution, this study shows that there were responses to vibrotactile stimuli in the region of the auditory cortex, but it could not be localized definitively to this area.

In another study, Schurmann et al. (2006) used fMRI, a tool which has a spatial resolution on the order of millimeters, in humans to show that different types of tactile stimuli activated auditory cortex. The auditory stimulus used in this study consisted of 500ms auditory broad-band noise delivered binaurally through headphones at 85 dB SL and the tactile stimulus consisted of one of two types: 500 ms bursts of 200 Hz vibrotactile stimuli delivered via silicone tubes at 20 dB SL and pulsed-tactile stimuli of 282 ms duration at a level specified as being well above the subjects' detection threshold. The authors imaged the subjects while presenting auditory alone contrasted with quiet, vibrotactile alone contrasted with vibrations given to a tube that was not being touched by the subject, and pulsed-tactile contrasted with no tactile signal. The authors found that the auditory stimulus elicited robust responses in the auditory cortex bilaterally and that the vibrotactile and pulsed-tactile stimuli elicited responses in the contralateral somatosensory cortex as well as in areas of the superior temporal gyrus posterior to the peak area of auditory activation. The authors also found an area of auditory and vibrotactile co-activation (overlap of the two response areas) in the location of the auditory belt area, posterior to the primary auditory cortex although this overlapped area did not show any pulsed-tactile-auditory co-activated responses. By showing good spatial localization of responses within secondary auditory cortex to vibrotactile stimuli, this study complements the previous MEG study, which showed good temporal resolution but poor spatial localization of auditory cortex and vibrotactile stimuli. The authors of this study also suggest that the overlapped area showing auditory-vibrotactile co-activation is a human homologue of the area CM found to be multisensory in macaque monkeys.

1.4.2 Integration

While the studies reviewed above have demonstrated that the auditory cortex responds to non-auditory stimuli, other work has shown that when the auditory and somatosensory stimuli are presented simultaneously the resulting response is greater than the sum of the two individual-sense responses, which is a classical definition of integration. In a study of this type, Kayser et al. (2005) used fMRI on anesthetized macaque monkeys to show auditory cortical responses to simultaneous auditory and tactile stimuli whose activation pattern was greater than the sum of the individual sensory responses (i.e. "super-additive"). The auditory stimuli were broad band noise bursts presented binaurally over headphones at 100 and 90 dB SPL and tactile stimuli consisted of a bristle-brush that rotated at 1.5-2 Hz against the monkey's hand or foot. The authors found that secondary auditory cortex showed activation in response to tactile alone, auditory alone, and combined auditory and tactile stimulation and that the extent and strength of the activation in the auditory cortex was greater for the combined stimulus condition than for the single sense responses. Additionally, they identified a subset of the auditory cortex which showed a response that was greater in the combined-sense paradigm compared with the sum of the individual senses, and that the integration pattern was strongest for temporally coincident stimuli. The site of integration was similar to that found in the studies mentioned earlier, namely the area CM of the auditory cortex. The authors also showed that the somatosensory cortex responded to the combined auditory and tactile stimuli but that this response was not significantly greater than activation seen with tactile alone.

In another study, Lakatos et al. (2007) used CSD and MUA to measure responses in primary auditory cortex to both auditory and somatosensory inputs in the macaque monkey. Unlike previous studies which showed tactile responses in secondary auditory cortex, this study was guided by recent anatomical findings which show somatosensory projections to primary auditory cortex. Their stimuli consisted of auditory clicks presented binaurally at 40 dB SPL and auditory clicks presented at 7 intensities ranging from 20-80 dB SPL. The auditory stimulus was either presented alone or in conjunction with somatosensory stimulation (electrical stimulation of the median nerve). The somatosensory stimulus always preceded the auditory and was presented at systematically varied stimulus onset asynchronies. The authors found tactile and combined auditory-tactile responses in the supra-granular layer of primary auditory cortex, a layer which is believed to be responsible for modulating (through inhibition) the excitatory activity in the input layer of the auditory cortex. The responses to combined stimuli were larger than the sum of the individual sense stimuli in the supra-granular layer when the auditory stimulus was between 20 and 40 dB SPL. When the auditory level was between 50-80 dB SPL, however, the auditory response dominated the combined-sense pattern. The authors also tested responses to combined auditory-tactile stimuli whose temporal onset was systematically staggered such that the tactile stimulus preceded the auditory stimulus (at 40 dB SPL) by amounts that were equally spaced logarithmically ranging from 0 (simultaneous) to 1220 ms. The authors found that the response to simultaneous auditory-tactile presentation was greater than the sum of the individual responses (i.e., showing integration). Additionally, at time intervals corresponding roughly to theta, gamma and delta wave activity (4-8, 40-70, and <= 2 Hz respectively), the data from the temporally staggered experiment showed response peaks that were close to the response amplitude to the simultaneous auditory-tactile stimulus. They also found troughs in response amplitudes at time intervals in between the peak responses. The authors suggest that the function of the somatosensory inputs to the supra-granular layer in primary auditory cortex is to modulate auditory activity in that layer, which in turn would modulate the activity in the input layer. They also suggest that this modulation of auditory by somatosensory inputs is dependent on the timing difference between them, such that when that time interval corresponds to an inherent neuronal rhythm (i.e., gamma, theta or delta wave), the response amplitude is significantly increased above auditory alone (i.e., the modulation is facilitatory). The authors suggest that the tactile inputs to the auditory cortex help to reset the internal phase of the oscillations of spontaneous activity in primary-AC making the neurons there more receptive to subsequent auditory input. When the timing of the two inputs is halfway between one of these neuronal rhythms, however, the response amplitude is significantly decreased compared with auditory alone (i.e., showing inhibition). This study is unique in that it shows somatosensory responses in the primary auditory cortex of a primate and that these responses interact with the concurrent auditory responses in a meaningful way.

These studies are important in establishing that areas of auditory cortex in both humans and non-human primates are capable of responding to stimuli from another sensory modality. Additionally, the integration studies show that not only was auditory cortex capable of responding to tactile stimuli, but that these response patterns could be greater than the sum of the individual auditory and tactile responses.

1.5 Perception

The studies reviewed here show that the interaction of the auditory and tactile systems is also manifested perceptually. Some of the following experiments show that the auditory stimulus can influence the perception of the tactile stimulus, and conversely, that the percept of an auditory stimulus can be modified by a tactile input. The methods used to measure subjects' perception include both objective and subjective procedures.

1.5.1 Influence of Tactile Stimulation on Auditory Perception

This section will review studies which explore the effect of a tactile stimulus on the perception of an auditory stimulus. Caclin et al. (2002) measured how auditory localization judgments were affected by the presence of a tactile distracter. This study presented auditory and tactile signals in the same interval and studied the effects the tactile sense had on the auditory judgments. Auditory stimuli were 15 ms bursts of 2000 Hz tones presented over speakers, and whose sound-source location was simulated by manipulating the interaural time and intensity differences between the pulses. A 200 Hz, supra-threshold vibrotactile stimulus was delivered to the index finger of each hand via a tactile device which was placed directly in front of the subjects and spaced halfway between the two speakers. In the first experiment, the auditory and tactile stimuli were presented simultaneously and auditory signal location was simulated using both time and intensity differences at each speaker. When the tactile stimulus was presented in combination with the auditory, the subjects perceived the auditory location as being closer to the tactile stimulus (midline) compared with when the auditory was presented alone. In the second experiment, the authors used only time differences between the speakers to simulate auditory signal location and presented the tactile stimulus at a time that was temporally offset from the auditory. For all stimulus onset asynchronies, the effect of shifting the auditory signal location to the midline was significantly diminished.

In another study, Schurmann et al. (2004) used a loudness matching paradigm to measure subjects' perceptions of auditory loudness between an auditory reference tone and an auditory probe tone presented alone or paired with a tactile vibration to the fingertips. The auditory stimulus used was a 200 Hz pure tone (in a background of white noise at 60 dB SL) and presented at 10 dB above masked threshold. The probe tone was of the same frequency as the reference tone and the intensity was adjusted by the subject during trials of probe-alone and probe-tactile. The tactile stimulus consisted of 200 Hz vibrations at 24-28 dB SL delivered to a tube held in the subjects' left hand fingers and in temporal synchrony with the auditory probe tone. Their results showed that the average intensity adjustment of the auditory probe tone was 12 % lower under the combined auditory-tactile condition compared with the auditory alone condition. The inter-subject variability was high, however, with one subject having greater than 12% difference, while the remaining eight subjects showed minimal or no differences between the two conditions.

Soto-Faraco et al. (2004) looked at the effects of cross-modal distraction during an auditory and tactile motion experiment. Their stimuli included 250 ms bursts of auditory tones at one of three different frequencies (450, 500 and 550 Hz) and two 50 ms bursts of vibrotactile stimulation (220 Hz) to the index finger of each hand. The auditory stimuli were presented from 2 speakers spaced 30 cm apart (one on each side of the subjects' midline) and from tactile devices that were placed in front of the speakers. The tests consisted of four combinations of auditory-tactile motion presentations, namely:

"synchronous congruent" in which the auditory and tactile stimuli occurred with the same temporal onset and traveled in the same direction (left to right or right to left). The second condition was "synchronous conflicting" in which the auditory and tactile stimuli occurred with the same temporal onset but occurred in opposing directions (i.e., the auditory stimulus was presented from left to right and the tactile stimulus was presented from right to left). The third condition was "asynchronous congruent" in which the auditory and tactile stimuli proceeded in the same direction, but with onset of the tactile relative to auditory stimulus delayed by 500 ms. The last condition was "asynchronous conflicting" in which the auditory and tactile stimuli were presented in opposite directions and with onsets of tactile relative to auditory stimulus delayed by 500 ms. The subjects' task was to denote the direction of the target stimulus and, on half of the trials, subjects were instructed to attend only to the auditory stimulus (auditory-target/tactile-distracter) and in the other half of trials were instructed to attend only to the tactile stimulus (tactile-target/auditory-distracter). The auditory-target/tactile-distracter experiment was then repeated with the subjects' arms crossed. Their results showed that when the two sensory cues were in temporal synchrony, the tactile stimulus was an effective distracter for the auditory target when they were in conflicting directions, causing a statistically significant reduction in percent correct auditory scores compared with congruent-direction presentation. When the task was reversed (tactile-target/auditory-distracter) there was a non-significant drop in percent correct score when the two sensory cues were temporally synchronous but with conflicting direction, compared with the congruent direction case. In both cases, when the stimuli were not in temporal synchrony, the presence of the distractor had no effect on performance. When the auditory-target/tactile-distracter study was repeated with the arms crossed, the results from the temporally synchronous condition showed a reduction in percent correct scores when the two stimuli were in the same perceived direction, and an increase in percent correct score when the two stimuli were in opposing perceived directions. These results were opposite of those found when the arms were uncrossed. The authors used the results from these experiments to suggest that a temporally synchronous tactile stimulus is an effective distracter for the auditory motion experiment, and that the disappearance of the effect when the arms are crossed suggests that the frame of reference is somatotopic (i.e., internal) versus external.

Gillmeister and Eimer (2007) studied the effect of tactile pulses on the detection and perceived loudness of auditory tones. The first experiment examined the effect of a 50 ms tactile pulse (3 mm, 1 Newton) on the detection of a 50 ms 466 Hz auditory tone (delivered via speaker). The tactile stimulus was presented at three different onset asynchronies (200 ms before auditory, simultaneously, and 200 ms after auditory) and in both temporal intervals of a 2I, 2AFC procedure. The auditory stimulus was presented at one of three different intensity levels (31, 32 and 33 dB SPL) within a background of white noise (at 53.5-60.2 dB SPL). The subjects' task was to detect the presence of the auditory signal in one of two temporal intervals (selected at random). The authors found that at 32 dB SPL, the simultaneous auditory-tactile presentation led to an improvement of roughly 5 percentage points over the percent correct score obtained in the non-simultaneous conditions. At 33 dB SPL, a decrease of 5 percentage points was observed when the tactile stimulus was presented 200 ms after the auditory stimulus compared with the simultaneous and tactile-preceding-auditory conditions. The 31 dB SPL condition did not show any change across any of the three temporal presentations. Although the authors demonstrate that temporal synchrony is an important factor in increasing the response to the combined stimuli, they did not perform a baseline experiment in which the ability to detect the auditory or tactile stimulus was tested in isolation. Thus, while a relative increase in performance is shown (based on a comparison of simultaneous versus non-simultaneous auditory-tactile presentations), without knowing the baseline percent-correct scores for the stimulus presented in isolation, it is not possible to know whether the tactile stimulus aided the detectability of the tone for synchronous conditions. The second experiment examined the effect of a tactile stimulus on the perceived loudness of an auditory signal. They measured the loudness of the tone as a subjective ranking on a 9-point scale. The auditory stimulus was presented either in isolation (at one of seven intensity levels) or with a tactile stimulus that was in temporal synchrony or offset temporally by 200 ms (tactile first). The authors found that synchronous onsets yielded a greater perception of overall loudness at the lowest three intensities (64, 65 and 66 dB SPL) and no change at the higher intensities and that asynchronous auditory-tactile presentation caused no change in perception of auditory loudness compared with the auditory alone condition.

1.5.2 Influence of Auditory Stimulation on Tactile Perception

Gescheider et al. (1969) measured tactile thresholds in the presence of auditory clicks using a 2-interval, alternative forced choice (2-I, AFC) procedure in which both detectability and bias could be estimated. The tactile stimulus was a brief tap to the right index finger presented at -4, -2, 0, and 2 dB SL, and the auditory signal was a click presented binaurally over headphones at intensities of 20, 50, and 80 dB SL (for a total of

16 conditions). For each tactile stimulus level, performance in d-prime decreased as the auditory click level increased, resulting in a maximum threshold increase of roughly 1.0 to 1.5 dB in the presence of the clicks.

Gescheider et al. (1974) examined the effects of the presence of a 500 Hz auditory tone (at 80 dB SPL) on the detection of a 500-Hz, 1 second vibration presented to the fingertip in a 1-I, 2AFC procedure. In a condition where the auditory tone was presented at a probability of 0.5 (and independent of the probability of a tactile presentation), the detectability of the tactile signal was the same in tone versus non-tone trials. In another task, subjects estimated the magnitude of the vibratory stimulus at 8 levels between threshold and 20 dB SL in the presence or absence of an 80 dB tone. The tactile stimulus was judged to be of higher magnitude in the presence of the tone at all values of SL, suggesting enhancement of the tactile sensation by the auditory stimulus.

Jousmaki and Hari (1998) showed that when the high frequency components (> 2 kHz) of an auditory signal were amplified by 15 dB a percept of dry palmar skin resulted when subjects rubbed their hands together. When the auditory signal was delayed by more than 100 ms relative to the tactile signals, the effect was significantly diminished. This experiment was later reproduced in greater detail by Guest et al. (2002) who used an apparatus in which the subject placed a hand into a box on which there was a rotating disc with different types of sandpaper to elicit the percepts of "smoothness" and "roughness." The auditory stimulus was the feedback of the sound of the hand being rubbed against the sandpaper and was presented in multiple ways: unmodified, high frequency (2-20 kHz) attenuated by 12 dB, or high frequency amplified by 12 dB. In a subsequent procedure the auditory stimuli were delayed by 150 and 300 ms relative to the onset of the tactile stimulus. Subjects were asked to identify whether or not the tactile stimulus was rough or smooth and responses were compared against the actual sand paper grain being presented. The results from the first experiment showed that there was a significant change in the proportion of errors in identifying the smoothness of the samples when the intensity of the high frequency auditory components was either attenuated or amplified compared with the unmodified auditory signal. Specifically, when the high frequency components were amplified the subjects perceived that the smooth samples were rougher; when the high frequencies were attenuated, the subjects perceived a smoother surface, both compared with the unmodified auditory signal. Their results suggest that auditory feedback was a key component in making tactile decisions about the perceived texture of the tactile stimulus. When the auditory feedback was delayed, the authors found that changing the auditory stimulus had little effect on the judgments made about the perceived smoothness of the tactile stimuli, thus showing that temporal synchrony was important in auditory-tactile integration.

Bresciani et al. (2005) used auditory beeps and tactile taps to show that under certain circumstances an auditory stimulus can affect the quantity of tactile taps perceived by the subject. Their auditory stimuli consisted of a series of three 50 ms bursts of 790 Hz tones at 74 dB within a background of white noise presented at 71 dB. The delay between auditory tone bursts was adjusted so that there was temporal coincidence between the onsets of the first and last tactile tap. The tactile stimuli were 20 ms taps presented at a level above threshold (1N, indenting skin 2mm via metallic pin 1mm in diameter). The subjects were told that the auditory and tactile stimuli were not related to one another, and were asked to judge the number of tactile taps they perceived. The number of auditory beeps was varied to include the following conditions: no auditory stimulus, one more beep than tap, same number of beeps and taps, one less beep than tap. The authors found that the auditory stimuli significantly affected the percept of the tactile tap, such that when presented with one more beep than tap, the subjects perceived an additional tap when one was not actually present. This result was found when the number of beeps was 3 and 4, but not when it was 2. The authors also found that the bimodal effects seen when the auditory and tactile stimuli were in temporal synchrony with one another were significantly diminished when there was a 200 ms delay between the two stimuli.

Two recent perceptual studies have reported effects of frequency on auditory-tactile interactions in tactile frequency-discrimination tasks performed in the presence of auditory "distracter" tones (Ro et al., 2009; Yau et al., 2009). Ro et al. (2009) examined the ability to discriminate between 100-Hz and 200-Hz vibratory stimuli using a 1-I, 2AFC procedure for stimulus presentations that included tactile stimulation alone and tactile stimulation in conjunction with a synchronous auditory tone of 100 or 200 Hz. The tactile stimuli were 250-msec in duration and were presented at levels that were subjectively matched to produce a "moderately intense percept" through a piezoelectric element at the dorsal surface of the left hand. The auditory stimuli, which were also 250-msec in duration, were presented through a loudspeaker located in front of the subject's left hand at a level of roughly 60 dB SPL. The mean hit rates were 0.62 for the tactile-alone stimulus presentations, 0.74 for presentations with equal-frequency auditory and tactile tones, and 0.43 for presentations with different-frequency auditory and tactile tones. Thus, performance was aided by the presence of auditory tones matched in frequency to the tactile sinusoids but declined in the presence of incongruous auditory tones. In fact, performance appears to be substantially worse than that expected on the basis of chance alone for the incongruous conditions. For the 200-Hz tactile, 100-Hz auditory condition, the hit rate was only 0.37, suggesting that subjects were able to discriminate the stimuli but reversed their corresponding response labels of "high" and "low". Thus, the 100-Hz auditory tone appears to have lowered the perception of the higher-frequency tactile signal..

Yau et al. (2009) used a 2I, 2AFC procedure to measure frequency discrimination for 1-s sinusoidal tactile signals presented to the right index finger. For a 200-Hz standard tactile stimulus (delivered over a contactor with 1-mm diameter), tactile comparison stimuli were seven sinusoids that were equally spaced in frequency over the range of 100-300 Hz and whose levels were equated for perceived intensity with the 200-Hz standard (whose level was 11.2 μm). On most trials of the experiment, an auditory tone (one of 8 values in the range of 100-1500 Hz with individual-tone levels in the range of 56.5-76.4 dB SPL selected to be equated for loudness) was presented synchronously with the comparison stimulus. (Although absolute thresholds for the tactile and auditory stimuli were not reported in this study, it is reasonable to assume that all signals were substantially above threshold.) The remaining trials, conducted without the auditory "distracter" tones, were used to establish baseline performance for the tactile frequency-discrimination task. The psychometric functions showed a significant reduction in sensitivity (i.e., ΔF for 73%-correct performance) compared to baseline performance only for those auditory distracters that were less than or equal to 300 Hz and a significant change in bias (i.e., the point of perceived subjective equality) for auditory distracters of 100 Hz only. An analogous frequency-discrimination experiment conducted with a 400-

Hz tactile standard stimulus (delivered over a contactor with 8-mm diameter at a level of 1 μm) indicated a significant reduction in sensitivity for auditory distracters in the range of 100-400 Hz and changes in bias for auditory tones of 100-300 Hz. Thus, these results suggest a significant interaction between auditory and tactile stimuli that are similar in frequency in performing a tactile frequency-discrimination task. No such effects of the frequency of auditory distracter tones were observed, however, in a tactile intensity-discrimination task employing either a 100-Hz standard (at a level of14.2 μm and comparisons in the range of 7.1-21.4 μm) or a 200-Hz tactile standard (at a level of 7.6 μm and comparisons in the range of 3.8 to 11.5 μm). The psychometric functions derived from trials with each of the auditory distracter frequencies were non-distinguishable from those of the baseline trials with no auditory distractors.

1.6 Significance and Hypotheses

Although there is increasing anatomical and physiological evidence that tactile and auditory stimuli interact with one another, there is much less direct perceptual evidence for this interaction. The significance of the research presented in this thesis is its systematic investigation of the perceptual integration of auditory and vibrotactile stimuli through a series of (a) detection measurements conducted with stimuli at levels near threshold and (b) loudness-matching measurements conducted with supra-threshold stimuli. Systematic and objective studies exploring the perceptual characteristics of auditory-tactile interactions are necessary both for interpreting the perceptual significance of results obtained in neurophysiological studies and for providing the impetus for future neurophysiological investigations.

In the detection studies, the measure of performance was a percentage-correct score, or d-prime (d'), which was used to compare performance in a combined auditory-plus-tactile presentation condition to the same measurement obtained in auditory-alone and tactile-alone conditions. The detection experiments (all conducted at levels near threshold) explored perceptual integration as a function of (a) relative phase, (b) relative temporal synchrony, (c) relative frequency, and (d) relative intensity of auditory and vibrotactile sinusoidal signals. The hypothesis of the detection studies states that if there is integration of the auditory and tactile stimuli, the measures of performance will be greater in the combined condition than in either of the separate presentation conditions. The amount of integration can be quantified by comparing performance in the combined conditions with the predictions of three models of the integration process. The Optimal Single Channel Model assumes that the observers' responses are based on the better of the tactile or auditory input channels and that the combined d' is simply the greater of the single-sense d' values. The Pythagorean-Sum Model assumes that integration occurs across channels and that the combined d' is the Pythagorean sum of the d-prime's for the separate channels. The Algebraic-Sum Model assumes that integration occurs within a given channel and that the combined d' is the sum of the d-prime's for the separate channels. Predicted measures of performance according to the Optimal Single Channel Model are never greater than the Pythagorean-Sum Model which, in turn, are never greater than for the Algebraic-Sum Model.

The loudness-matching experiments were included to explore perceptual integration for supra-threshold stimuli. These studies employed an auditory tone as a comparison stimulus whose loudness is adjusted to match that of various combinations of auditory and tactile stimuli. The hypothesis for these studies is derived from auditory research on the growth of loudness for stimuli within the same or different critical bands (e.g., Zwicker, Flottorp, and Stevens, 1957). Specifically, less loudness growth is observed for two stimuli within the same critical band compared to two stimuli located within two separate critical bands. Thus, our hypothesis predicts that the level of a comparison tone that is needed to match the loudness of a combined auditory-tactile signal will be larger when auditory and tactile stimuli are detected in separate channels than when they are detected within the same channel. Loudness growth should be less for auditory-tactile stimulus combinations that obey the Algebraic-Sum Model of integration compared to those that obey the Pythagorean-Sum Model of integration. It should be noted that this prediction is counterintuitive compared to the opposite direction of the predictions made for detection of near-threshold signals. This experiment has significant implications for the results of neurophysiological studies conducted at supra-threshold levels which do not demonstrate evidence for bimodal integration present at levels close to threshold.

1.7 General Methodology

This thesis consists of experimental research in two major areas: (1) studies of detection of auditory and tactile stimuli at levels near threshold and (2) studies of loudness matching employing combinations of auditory and tactile stimuli at supra-threshold levels. General methods used for software development and for experimental set-up and subjects are described in Sections 1.7.1, 1.7.2, and 1.7.3 below. Methodology specific to the detection experiment will be described in Sections 1.8.1, 1.8.2 and 1.8.3

and methods specific to the loudness matching experiment will be described in Section 1.9.

1.7.1 Software Development

The software used in these experiments is written and executed in Matlab and uses the program “afc_main 2006.” The afc_main front end routines (the _cfg, _set, and _user files) have been modified in order to accommodate both auditory and tactile stimuli. This was done by using the “stereo” feature of Matlab in which the left channel has been dedicated to the tactile stimulus and the right channel has been dedicated to the auditory stimulus.

1.7.2 Experimental Set-Up

Figure 5 shows the experimental setup used in all runs. Since it has been found that tactile thresholds vary as a function of temperature (Weitz, 1941; Gescheider et al., 1997), a heating pad has been placed inside of the box containing the tactile device in order to provide constant temperature inside the box and on the metal portions of the tactile device that vibrate against the fingertip.

In all stimulus presentations, there is a background auditory broad band noise (50 dB SPL for detection experiment and 55 dB SPL for loudness matching experiment) which precedes onset of the actual signal intervals by 100 ms and continues for 100 ms after offset of the signals (to mask any auditory artifact from the tactile device).

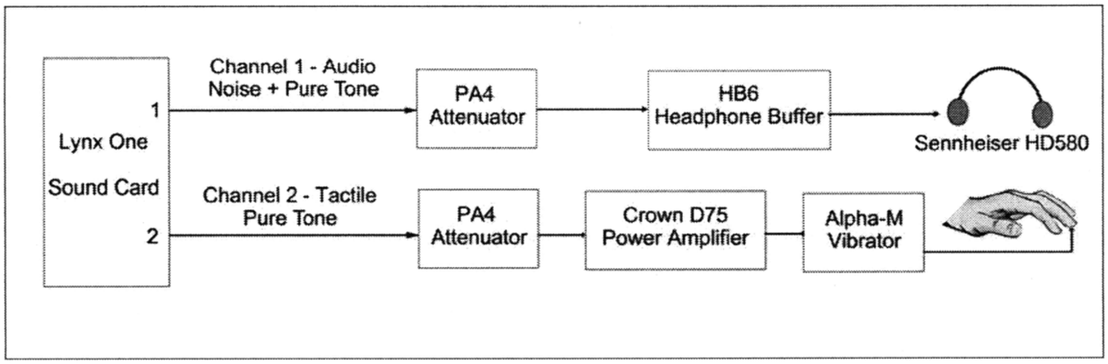

Figure 5 Diagram showing the experimental setup for the stimulus delivery. The auditory, tactile or combined stimulus is delivered through the sound card, and is separated into two channels, one for audio and one for tactile. The auditory stimulus is attenuated by 30 dB and output to deliver a binaural signal through the HD 580 headphones. The tactile stimulus is amplified until the signal is 0.75 Volts rms (250 Hz signal, and equivalent displacement for other tactile frequencies). The amplified tactile signal is sent to the alpha-M vibrator which is in contact with the subjects' left middle fingertip.

1.7.3 Subjects

Normal-hearing subjects (18 years of age and older) are recruited from the general Boston community. Audiometric testing is performed to determine that subjects have normal hearing (20 dB HL or less in the frequency range of 125 – 8,000 Hz). For each subject, at least 4 sessions of actual data are recorded (in addition to 3 training sessions) and a typical experiment employs approximately 4-6 subjects to complete the data set.

1.8 Detection Experiments

1.8.1 General Methods

Experimental methods include adaptive and constant stimuli measurements. Adaptive thresholds are estimated using the Levitt (1971) up-down method in a 3-interval, 2-alternative forced choice paradigm (3-I, 2AFC), converging at the 70.7% correct mark after six reversals.

The masked auditory and absolute tactile threshold levels derived from the adaptive procedure are then employed in a constant stimulus procedure, which uses a 2-interval, 2-alternative forced choice (2-I, AFC) paradigm. Acceptable threshold percent correct values obtained on any 75-presentation run range between 63% and 77%-correct (i.e., ± 1 standard deviation around 70%-correct), and both auditory and tactile values should be within a few percentage points of one another so as to avoid the possibility of one sense dominating the other. The stimulus levels are adjusted accordingly until these criteria are met. The combined stimuli are then presented in a 2-I, 2-AFC Constant Stimuli experiment, where a single run consists of 75 trials. On each trial, the signal is presented in one of the two temporal intervals (selected at random), and the subject's task is to determine which of the two intervals contains the signal.

In order to help maintain attention in the combined task, subjects are instructed to count how many times they perceive a signal and to increment that count only when the program's feedback states that their selected interval was the correct one. The subject's final count has no bearing on the actual calculation of the percent correct score and it does not play any part in the data analysis.

Each experimental session lasts no more than two hours on any given day (to prevent fatigue). Additionally, in order to help mitigate fatigue during the 2 hour session, after each run subjects are required to leave the booth and retrieve the experimenter in order to set up the next run. This enables the subject to move around and to get some fresh air after each ~7 minute run. Typically, trained subjects are able to complete a threshold estimation test in approximately one hour (two adaptive runs per sense, plus as many constant stimulus runs per sense as needed to determine the threshold within our given %-correct range). The remainder of the session is used to test parameters for the combined-sense experiments. The time between each session should be no longer than one week in order not to lose any effect of the training.

At the end of each session, the auditory and/or tactile thresholds may be re-tested using the 2-I, 2-AFC Constant Stimulus method in order to confirm that the threshold has not shifted during the course of the experiment. If the threshold has shifted more than 2 standard deviations (i.e., percent correct scores less than 56% or greater than 84%, assuming the threshold was at or near 70% to begin with), the data for that session are discarded. Subjects are disqualified if, after the three training sessions, they have more than two sessions in which their thresholds have shifted outside the acceptable range.

1.8.2 Data Analysis

This work presented in this thesis employs the use of signal detection theory in order to objectively test the subjects' perceptions and analyze the data. The experimental results are summarized in terms of a two-by-two stimulus-response matrix containing the number of times the subject correctly and incorrectly identified the order in which the signal and the noise were presented (see table below). The presentation is a two interval forced choice in which one of two stimulus orders may be presented randomly: the signal in interval one followed by noise in interval two or noise in interval one followed by the signal in interval two. The experimental results are tabulated as described in the table below. For each possible stimulus/response combination, the n_{ij} value represents the number of times the subject made that particular response out of the total number of presentations (sum of all n_{ij}).

Stimulus**Response**	*Signal, Noise*	*Noise, signal*
Signal, noise	Correct Signal Detection (**P_d**) (n_{11})	Error (n_{12})
Noise, Signal	False Alarm (**P_f**) (n_{21})	Correct non-signal Detection (n_{22})

% correct = $(n_{11}+n_{22})/(n_{11}+n_{12}+n_{21}+n_{22})$

$P_d = n_{11}/(n_{11}+n_{12})$

$P_f = n_{21}/(n_{21}+n_{22})$

P_d *: the probability that the subject responds S,N given trials with S,N*

P_f*: the probability that the subject responds S,N given trials with N,S*

S: Signal, in the auditory case the Signal is a tone presented in broadband noise, and in the tactile case the Signal is a sinusoidal vibration. In the combined sense, Signal is Auditory tone in background noise and Tactile vibration presented in the same interval.

N: Noise, in the auditory case, N is broadband noise, in Tactile case, N is an empty interval.

Z_d*: Inverse of the normal cumulative distribution function with probability* P_d

Z_f*: Inverse of the normal cumulative distribution function with probability* P_f

$d' = Z_d - Z_f$, $\beta = -(Z_d + Z_f)/2$

An arcsine transformation may be applied to the percent correct scores prior to statistical analysis in order to normalize the data. Data analysis is then performed on the values listed above (including raw values and transformations) and includes performing statistical comparisons of these values across the different parameters being tested. For example, one- or two-way analysis of variance tests (ANOVA) or paired t-tests may be employed in analyzing the data for statistical patterns.

1.8.3 Models of Integration

The results of the experiments are compared with three different models of integration. The Optimal Single Channel Model assumes that the observers' responses are based on the better of the tactile or auditory input channels. The predicted d-prime for the combined A+T condition is the greater of the tactile (d'_T) or auditory (d'_A), i.e., Max(d'_T, d'_A). The Pythagorean-Sum Model assumes that integration occurs across channels (e.g., as in audio-visual integration, Braida, 1991) and that the d' in the combined auditory-tactile condition is the Pythagorean sum of the d-prime's for the separate channels. For example, the d' resulting sum would be $\sqrt{d'^2_A + d'^2_T}$. The Algebraic-Sum Model assumes that integration occurs within a given channel and that the combined d' is the simple sum of the d-prime's for the separate channels. For example, the resulting sum would be $d'_A + d'_T$. Performance predicted by the Optimal Single Channel Model is never greater than that predicted by the Pythagorean-Sum Model, which is never greater than that predicted by the Algebraic-Sum Model.

1.9 Loudness Matching Experiments

1.9.1 General Methods

The stimuli in this set of experiments are presented at levels that have been matched in loudness to a common reference. In order to establish these levels, estimates of the auditory masked thresholds for pure tones in 55-dB SPL broadband noise and for tactile thresholds (also presented with the 55-dB SPL auditory broadband noise) are measured adaptively using a 2-I, 2-AFC, converging at the 70%-correct mark (Levitt, 1971). Next, the auditory and tactile pure tones are matched in loudness to (what will become) the auditory probe tone that is set at 25 dB SL. The levels established in this procedure are to be used in subsequent combined presentations. A 2-I, 2AFC procedure was used to obtain the loudness matches. For the actual experimental conditions, one interval (selected at random) contained the 200 Hz auditory probe tone and the other interval contained the reference stimulus. The subject's task was to determine, on each trial, which of the two stimuli was "stronger." This experimental procedure also interleaved two tracks, one in which the initial probe level was set high and one in which the initial probe level was set low; the presentation of the two tracks was interleaved and presentation of the tracks was randomized. The level of the probe was adjusted adaptively, as described in Silva & Florentine (2006) and Jesteadt (1980). The loudness match was determined by averaging over the probe stimulus levels for the last 6 reversals of level in the adaptive procedure. The experiment consisted of multiple repetitions of 1) establishing the levels of the single tones (both auditory and tactile tones matched to the 200 Hz probe set at 25 db SL) and 2) measurement of the probe level when compared with the reference stimulus.

In all presentations, the auditory background noise is present (broad band noise at 55 dB SPL). All auditory stimuli are presented binaurally over headphones and all tactile stimuli are presented to the left middle fingertip.

Chapter 2. Effects of Phase and Temporal Asynchrony on Auditory-Tactile Integration

The work described in this chapter is published in the *Journal of the Acoustical Society of America*

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ABSTRACT

The perceptual integration of 250 Hz, 500 ms vibrotactile and auditory tones was studied in detection experiments as a function of 1) relative phase and 2) temporal asynchrony of the tone pulses. Vibrotactile stimuli were delivered through a single-channel vibrator to the left middle fingertip and auditory stimuli were presented diotically through headphones in a background of 50 dB SPL broadband noise. The vibrotactile and auditory stimulus levels used each yielded 63-77%-Correct unimodal detection performance in a 2I-2AFC task. Results for combined vibrotactile and auditory detection indicated that 1) performance improved for synchronous presentation, 2) performance was not affected by the relative phase of the auditory and tactile sinusoidal stimuli and 3) performance for non-overlapping stimuli improved only if the tactile stimulus preceded the auditory. The results are generally more consistent with a "Pythagorean Sum" model than with either an "Algebraic Sum" or an "Optimum Single Channel" model of perceptual integration. Thus certain combinations of auditory and tactile signals result in significant integrative effects. The lack of phase effect suggests an envelope rather than fine structure operation for integration. The effects of asynchronous presentation of the

auditory and tactile stimuli are consistent with time constants deduced from single-modality masking experiments.

I. INTRODUCTION

Multisensory interactions commonly arise in everyday exploration of the environment and numerous examples can be cited to demonstrate the influence of one sensory modality over another. For example, the presence of an auditory signal can alter judgments regarding the intensity, numerosity, and motion of visual signals (Stein et al., 1996; Bhattacharya et al., 2002; Sekuler et al., 1997), and the location of a visual stimulus can modify the perceived location of an auditory signal (as in the ventriloquism effect; Woods and Recanzone, 2004). In the area of speech perception, for example, the McGurk effect (McGurk and MacDonald, 1976) provides a powerful demonstration of the ability of visual cues derived from lip-reading to influence the perception of auditory speech cues. The current research is concerned with exploring perceptual interactions between the senses of hearing and touch and is motivated by recent results from anatomical and physiological studies demonstrating significant interactions between these two senses.

In anatomical research, recent studies indicate that areas of the central nervous system that have traditionally been thought to receive auditory-only inputs may also receive inputs from the somatosensory system. For example, in the brainstem, the trigeminal nerve sends somatosensory input to the cochlear nucleus of the guinea pig (Zhou & Shore, 2004), while in the thalamus, somatosensory projections are sent to non-primary areas of the auditory cortex of the macaque monkey (Hackett et al., 2007).

Projections within the cortex have been found from the secondary somatosensory cortex to the primary auditory cortex of the marmoset monkey (Cappe & Barone, 2005) as well as to non-primary auditory cortical areas of the macaque monkey (Smiley et al., 2007). Additionally, recent physiological studies in humans (using non-invasive imaging) as well as in non-human primates (using electrophysiology) suggest that the auditory cortex is an active multisensory area, responding to somatosensory input alone as well as to combined auditory and tactile stimuli in a manner that is different from responses to auditory-only stimulation (Schroeder et al., 2001; Foxe et al., 2002; Fu et al., 2003; Caetano and Jousmaki, 2005; Kayser et al., 2005; Schurmann et al., 2006; Lakatos et al., 2007).

Although there is increasing anatomical and physiological evidence that tactile and auditory stimuli interact, there is less direct perceptual evidence for this interaction. Previous perceptual studies of auditory and tactile interactions can be organized into two broad categories: the influence of tactile stimulation on auditory perception and the influence of auditory stimulation on tactile perception. In the first category, experiments have shown that tactile stimuli can influence auditory localization (Caclin et al., 2002) and auditory motion (Soto-Faraco et al., 2004). Other perceptual studies have examined the effects of tactile stimulation on the perceived loudness or discriminability of auditory stimuli (Schurmann et al., 2004; Schnupp et al., 2005; Gillmeister and Eimer, 2007; and Yarrow et al., 2008). These studies employed a variety of experimental procedures (i.e., loudness matching, signal detectability, and signal discriminability) and, under certain experimental conditions, have shown increased loudness or discriminability for paired auditory-tactile stimuli compared with the single-modality stimulus.

In the second category, auditory stimuli have been effective in influencing tactile perception, including such examples as changes in tactile threshold or tactile magnitude when paired with an auditory stimulus (Gescheider et al., 1969; Gescheider et al., 1974; Ro et al., 2009). Other studies have shown that changing the high-frequency components of the auditory stimulus on a tactile task can affect the roughness judgment of the tactile stimulus (Jousmaki and Hari, 1998; Guest et al., 2002) and that judgments of tactile numerosity can be affected by the presence of competing auditory signals (Bresciani et al., 2005). In several of these studies (Soto-Faraco et al., 2004; Bresciani et al., 2005; Gillmeister and Eimer, 2007), temporal synchrony between the auditory and tactile stimuli was an important factor in eliciting interactive effects.

Further systematic and objective studies exploring the perceptual characteristics of the auditory and tactile systems are necessary for understanding the interactions between these sensory systems. In addition, perceptual studies will aid in interpreting the anatomical and neurophysiological studies which demonstrate significant interactions between the auditory and tactile sensory systems. The goal of the current research was to obtain objective measurements of auditory-tactile integration for near-threshold signals through psychophysical experiments conducted within the framework of signal-detection theory, using d' (and %-Correct) as a measure of detectability. Our hypothesis (derived from a general model proposed by Green, 1958) states that if the auditory and tactile systems do integrate into a common neural pathway, then the detectability of the two sensory stimuli presented simultaneously will be significantly greater than the detectability of the individual sensory stimuli. Specifically, if the stimuli are judged independently of one another, the resulting d' should equal the root-squared sum of the individual sensory d' values. If, on the other hand, the stimuli are integrated into a single percept before being processed, the resulting d' should equal the sum of the individual d' values.

The experiments reported here explore the perceptual integration between auditory pure tones and vibrotactile sinusoidal stimuli as a function of (1) phase and (2) stimulus-onset asynchrony. Manipulations of the relative phase of the tactile and auditory tonal stimuli were conducted as a means of exploring whether the interaction of the stimuli occurs at the level of the fine structure or envelope of the signals from the two separate sensory modalities. Manipulations of stimulus-onset asynchrony between the tactile and auditory signals were conducted to explore the time course over which cross-modal interactions may occur. Measurements of d' (and %-Correct) were obtained for auditory-alone, tactile-alone, and combined auditory-tactile presentations. The observed performance in the combined condition was then compared to predictions of multi-modal performance derived from observed measures of detectability within each of the two separate sensory modalities.

II. METHODS

A. Stimuli

The auditory stimulus employed in all experimental conditions was a 250-Hz pure tone presented in a background of pulsed 50 dB SPL Gaussian broadband noise (bandwidth of 0.1 to 11.0 kHz). The tactile stimulus employed in all experimental conditions was a sinusoidal vibration with a frequency of 250 Hz. The background noise was utilized to mask possible auditory cues arising from the tactile device and was present in all auditory (A), tactile (T), and combined auditory plus tactile (A+T) test conditions. The 250-Hz signals in both modalities were generated digitally (using Matlab 7.1 software) to have a total duration of 500 ms that included 20-ms raised cosine-squared rise/fall times.

The digitized signals were played through a D/A sound card (Lynx Studio Lynx One) with a sampling frequency of 24 kHz and 24-bit resolution. The auditory signal was sent through channel 1 of the sound card to an attenuator (TDT PA4) and headphone buffer (TDT HB6) before being presented diotically through headphones (Sennheiser HD 580). The tactile signal was passed through channel 2 of the sound card to an attenuator (TDT PA4) and amplifier (Crown D-75) before being delivered to an electromagnetic vibrator (Alpha-M Corporation model A V-6). The subject's left middle fingertip made contact with the vibrator (0.9 cm diameter). A laser accelerometer was used to calibrate the tactile device.

B. Subjects

Eleven subjects ranging in age from 18 to 48 years (five females) participated in this study. Audiological testing was conducted on the first visit to the laboratory. Only those subjects who met the criterion of normal audiometric thresholds (20 dB HL or better at frequencies of 125, 250, 500, 1000, 2000, 4000 and 8000 Hz) were included in the studies. All subjects were paid an hourly wage for their participation in the experiments and signed an informed-consent document prior to entry into the study. Six subjects participated in Experiment 1 (S_1, S_2, S_3, S_4, S_6, and S_7), four in Experiment 2A (S_6, S_8, S_9, and S_{10}), four in Experiment 2B (S_2, S_4, S_7 and S_8), and four in Experiment 2C (S_8, S_{10}, $S_{21,}$ andS_{24}). Six of the subjects participated in multiple experiments (S_2, S_4, S_6, S_7, S_8, and S_{10}).

An additional 11 subjects passed the audiometric criteria and began participation in the study but were terminated from the experiments on the basis of instability in their threshold measurements over the course of the two-hour test sessions. Further details of the criteria that were used for disqualifying a subject from continued participation in the study are provided below in Section D[1].

C. Experimental Conditions

The experiments examined the perceptual integration of 250-Hz sinusoidal auditory and vibrotactile signals that were each presented near the threshold of detection. Threshold measurements were first obtained under each of the two single-modality conditions (A and T separately). Then the detectability of the combined auditory plus tactile (A+T) signal was measured at levels established for threshold within each of the two individual modalities. The experimental conditions examined the effects of relative phase (Experiment 1) and stimulus-onset asynchrony (SOA, Experiments 2A, 2B, and 2C) of the tactile signal relative to the auditory signal.

A summary of the conditions employed in the two experiments is provided in Table 1. Throughout the experiments, the stimuli were 250-Hz sinusoids of 500 ms duration (including 20 ms rise/fall times). The stimulus parameters are described in terms of the starting phase of the auditory (column 2) and tactile (column 3) stimuli and SOA (column 4). Specifically, we define SOA to be: Onset Time $_{\text{Tactile}}$ - Onset Time $_{\text{Auditory}}$. Thus, the SOA is positive when the auditory stimulus precedes the tactile, 0 when the two stimuli have simultaneous onsets, and negative when the tactile stimulus precedes the

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[1] Data collected from an additional two subjects (S_5 in Experiment 1 and S_7 in experiment 2C) were discarded on the basis of abnormally low values of thresholds for the tactile stimuli that were inconsistent with those of the other subjects and with results in the literature.

auditory. Information concerning the subjects and the number of repetitions of each experimental condition is provided in the final two columns of Table 1.

Baseline Condition. A baseline condition employing 0-ms SOA and starting phase of 0° for both auditory and tactile stimuli was included in each of the experiments (Conditions 1-1, 2A-1, 2B-1, 2C-1 in Table 1). Performance on this baseline condition was generally measured as the first A+T condition in each test session for each subject under each of the four experiments.

Experiment 1. Experiment 1 examined the effect of the starting phase of the tactile relative to the auditory stimuli and is in described in Table 1 (Conditions 1-1 through 1-4). The auditory starting phase was always 0°, while the tactile starting phase took on four different values: 0, 90, 180 and 270°. In each of these four conditions, the auditory and tactile stimuli were temporally synchronous (0-ms SOA) and thus had identical onset and offset times. This experiment was conducted on six subjects; each completed six repetitions of each condition in 6 or 7 test sessions. The order of the 4 experimental conditions was randomized within each replication for each subject.

Experiment 2. Experiment 2 examined the effect of asynchronous presentation of the auditory and tactile stimuli and is described in Table 1 (Conditions 2A, 2B, and 2C). The starting phase of the auditory and tactile sinusoids was 0° throughout all of the conditions of Experiment 2. The presentation order of the experimental conditions in Experiments 2A, 2B and 2C was randomized across sessions for each of the subjects.

In Experiment 2A (Table 1, Conditions 2A-1 through 2A-7), the auditory stimulus preceded the tactile stimulus with six values of SOA in the range of 500 to 750 ms (i.e., there was never any temporal overlap between the two stimuli). Thresholds in the

Baseline condition (0-ms SOA) were also measured, for a total of 7 conditions. Four subjects completed four replications of each of the non-zero SOA conditions while the 0-ms SOA condition was measured at the start of each session (resulting in more than 4 measurements of this condition for some subjects). The number of test sessions required to complete the experiment ranged from 4 to 9 across subjects.

In Experiments 2B and 2C (Table 1, Conditions 2B-1 through 2B-7 and 2C-1 through 2C-8), the tactile stimulus preceded the auditory stimulus. In Experiment 2B, six values of SOA were studied in the range of -500 to -750 ms (there was no temporal overlap between the two stimuli), in addition to the baseline (0-ms SOA) condition. Four subjects[2,3] completed four replications of each of the 6 non-zero SOA conditions, requiring 4 to 9 test sessions. In Experiment 2C, in addition to the conditions described above for Experiment 2B, an SOA of -250 ms was included in order to examine the effect of partial temporal overlap between the two stimuli. Four subjects each completed four replications of the 7 non-zero SOA conditions. In Experiment 2C, one subject from Experiment 2B (S_8) returned to complete four repetitions of Condition 2C-2 (-250 ms SOA) and a partial subset of the remaining SOA values. Three additional subjects (S_{10}, S_{21} and S_{24}) completed 4 replications of the 8 experimental conditions in 5-9 sessions.

D. Experimental Procedures

For all experimental conditions, subjects were seated in a sound-treated booth and were presented 50 dB SPL broadband noise diotically via headphones. For testing in

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[2] Three subjects (S_2, S_4, and S_7) were also tested in two additional conditions in Experiment 1 (phase = 0°, SOA = +600 ms and SOA = -600 ms) in addition to the 4 phase conditions. These subjects later participated in Experiment 2B and SOA values of ± 600 ms were not repeated.

[3] Due to experimenter error, performance on the combined A+T (SOA = 0 ms) condition was not measured in several of the Experiment 2B test sessions for three subjects (S_2, S_4, and S_7), although performance on A-alone and T-alone conditions was always established at the beginning of each session.

conditions that involved presentation of the tactile stimulus (T and A+T), the subject placed the left middle finger on a vibrator which was housed inside a wooden box for visual shielding and sound attenuation. A heating pad was placed inside the box in order to keep the box and tactile device at a constant temperature.

The following protocol was employed for testing within each experimental session: (i) thresholds for each single-modality condition (A and T) were estimated adaptively (Levitt, 1971), (ii) fixed-level testing was conducted for A and T separately to establish a signal level for single-modality performance in the range of 63-77%-Correct, (iii) fixed-level performance was measured for the baseline A+T condition (0-ms SOA, 0°phase), (iv) fixed-level performance was measured in the experimental A+T conditions, and (v) single-modality fixed-level testing was repeated as in (ii) except with an expanded acceptable performance range of 56-84%-Correct. (Data from the second set of single-modality conditions was not otherwise used.) The number of experimental A+T conditions that could be completed within a given test session was dependent on the time required to establish signal levels that met the single-modality performance criterion.

A test session typically lasted two hours, during which performance was measured in fixed-level experiments for the A and T conditions and A+T conditions associated with a given experiment. For each subject, three training sessions identical to the experimental sessions were provided before data were recorded. If a subject participated in multiple experiments, the three training sessions were provided only prior to the first experiment (i.e., Subjects S_2, S_4, S_6, S_7, S_8 and S_{10} underwent only three training sessions even though they participated in multiple experiments). Attention to the combined A+T stimulus was ensured by having subjects count the number of times they perceived a signal. Each experimental session lasted no more than two hours on any given day and subjects took frequent breaks throughout the session.

If the single-modality threshold re-tests at the end of a given session were less than 56%-Correct or greater than 84%-Correct (± 2 standard deviations assuming an original score of 70%-Correct), the data for that session were discarded. The number of sessions discarded per subject ranged from 0 to 3 in Experiments 1 and 2A, 0-2 in Experiment 2B, and 0 in Experiment 2C. Subjects were terminated from the experiment if their scores shifted by more than 2 standard deviations in three non-training sessions, resulting in the disqualification of 11 subjects from participation in the study. Typically, disqualification resulted from increased variability in tactile threshold measurements. On average, the difference between scores measured at the beginning and end of a test session was 10.8 percentage points in the disqualified subjects compared to -0.6 percentage points in the retained subjects (with the differences in absolute values being 16.2 and 8.7 percentage points, respectively). Differences between disqualified and retained subjects were not as great for auditory scores: the corresponding differences were 4.8 and 3.0 percentage points (with the differences in absolute values being 7.5 and 6.6 percentage points, respectively).

2-I, 2-AFC Fixed-Level Tests. The adaptive threshold estimates under the single-modality A and T conditions were employed in a 2-I, 2-AFC fixed-level procedure with 75 trials per run. Stimulus levels were adjusted and runs were repeated until scores of 63-77%-Correct were obtained. These stimulus levels were then used in testing the combined A+T conditions with the fixed-level 2-I, 2-AFC procedure.

On each presentation, the tone (auditory, tactile, or auditory-tactile) was presented with equal *a priori* probability in one of the two intervals. The interval duration was 1.15 seconds for Experiment 1 and 1.25 seconds for Experiment 2. Each interval was cued by visually highlighting a push-button on the computer screen located in front of the subject. Noise was presented diotically over headphones starting 500 ms before the first interval, and played continuously throughout a trial (including the durations of the two intervals and the 500-ms duration between intervals) before being turned off 500 ms after the end of the second interval. Each trial had a fixed duration of 3.8 seconds (Experiment 1) or 4 seconds (Experiment 2), plus the time it took subjects to respond. The onset of the stimulus (A,T or combined A+T) was always coincident with the onset of the observation interval in which it appeared. Subjects responded between trials by selecting the interval in which they thought the stimulus was presented (using either a mouse or keyboard) and were provided with visual correct-answer feedback.

E. Data Analysis

A two-by-two stimulus-response confusion matrix was constructed for each 75-trial experimental run, and was used to determine percent-correct scores and signal-detection measures of sensitivity (d'). These measures were averaged across the repetitions of each experimental condition within a given subject. Statistical tests performed on the data included ANOVAs on the arcsine transformed percent-correct scores, with statistical significance level defined for probability (p-values) less than or equal to 0.01. For statistically significant effects a *post hoc* Tukey-Kramer analysis was performed with alpha = 0.05.

F. Models of Integration

The results of the experiments were compared with three different models of integration: The Optimal Single Channel Model (OSCM), the Pythagorean-Sum Model (PSM), and the Algebraic-Sum Model (ASM). The OSCM assumes that the observers' responses are based on the better of the tactile or auditory input channels. The predicted D'_{OSCM}[4] for the combined A+T condition is the greater of the tactile (d'_T) or auditory (d'_A), $D'_{OSCM} = \mathrm{Max}(d'_T, d'_A)$. The PSM assumes that integration occurs across channels (e.g., as in audio-visual integration, Braida, 1991) and that the d' in the combined auditory-tactile condition is the Pythagorean sum of the d-prime's for the separate channels, $D'_{PSM} = \sqrt{d'_A{}^2 + d'_T{}^2}$. The ASM, on the other hand, assumes that integration occurs within a given channel and that the combined d' is the linear sum of the d-prime's for the separate channels, $D'_{ASM} = d'_A + d'_T$. For example, if the auditory d'_A was 1.0 (69%-Correct) and the tactile d'_T was 0.8 (66%-Correct), the OSCM would predict a D'_{OSCM} of 1.0 (69%-Correct), the PSM would predict a D'_{PSM} of 1.28 (74%-Correct) and the ASM would predict a D'_{ASM} of 1.8 (82%-Correct). The OSCM prediction is never greater than the PSM prediction, which in turn is never greater than the prediction of the ASM.

Chi-Squared goodness-of-fit calculations were employed to compare observed with predicted values from each of the three models. The predictions of the models were evaluated as follows: First, d-prime values were determined for each auditory (d'_A) and tactile (d'_T) experiment, on the basis of 75 total trials. Second, predicted d-prime values were computed for the three models according to the formulas given above. Third, predicted %-Correct scores were computed for each of the models in the following

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[4] We denote d-primes that can be estimated directly from the data using lower case (d'), d-primes that are predicted by models by upper case letters (D').

manner: %-Correct = $100*\phi(\frac{D'_{A+T}}{2})$, where ϕ is the cumulative of the Gaussian distribution function, and D'_{A+T} is the predicted D'. Fourth, the observed A+T confusion matrix was analyzed to estimate d'_{A+T} and the "no bias" estimate of %-Correct score was computed as $\%_{A+T} = 100*\phi(\frac{d'_{A+T}}{2})$. This relatively small adjustment (1.6 percentage points on average, 13 points maximum) was necessary because the predictions of the models assumed that the observer is not biased. Predictions (D'_{OSCM}, D'_{PSM}, and D'_{ASM} or $\%_{OSCM}$, $\%_{PSM}$ and $\%_{ASM}$) were compared with observations (d'_{A+T} or $\%_{A+T}$). The proportion of the observations that agreed with predictions was judged by having a Chi-Squared value less than 3.841 (the 95% criterion) between predicted and observed scores (corrected as discussed above) using a contingency table analysis (Neville and Kennedy, 1964). This analysis allows for errors in both the observed score and the predicted score.

III. RESULTS

A. Signal Levels Employed in Single-Modality Conditions

Single-modality auditory and tactile thresholds were obtained both at the beginning and ending of each individual test session. The data reported here, however, are based solely on the initial measurements. Analyses that used the average of the beginning and ending single-modality measurements were not significantly different from these. Thus, we used the post-experiment measurements merely as a tool for determining threshold stability.

Levels for Auditory-Alone Conditions. The mean signal levels in dB SPL established for performance in the range of 63-77%-Correct for a 250-Hz tone in 50-dB SPL broadband noise are shown in the upper panel of Fig. 1. Mean levels of the tone are plotted for each individual subject in each of the four experiments. Each data point depicted in the plot is based on an average of at least 4 and as many as 11 measurements in the fixed-level 2-I, 2-AFC procedure (each of which yielded performance in the range of 63-77%-Correct). Ten of the eleven subjects had average auditory masked thresholds within a 2.1-dB range of 22.3 to 24.4 dB SPL. The remaining subject (S_{10}) had a value of 27.8 dB SPL, measured consistently across multiple sessions. Within a given subject, tonal levels were highly stable for measurements made within a given experiment and across experiments. Values of ± 2 SEM (accounting for 96% of the measurements) ranged from 0.095 to 1.1 dB across subjects and experiments.

These results are consistent with those obtained in previous studies of tonal detection in broadband noise. Critical ratios were calculated for the tone-in-noise levels shown in Fig. 1 by subtracting the spectrum level of the noise at 250-Hz (which was 7.4 dB/Hz) from the presentation levels of the 250-Hz tone. Across subjects and experiments, mean critical ratios ranged from 14.9 to 20.4 dB and are consistent with the critical ratio value of 16.5 dB at 250 Hz reported by Hawkins and Stevens (1950). Thus, these results indicate that subjects were listening to the auditory tones in noise at levels that were close to masked threshold.

Levels for Tactile-Alone Conditions. The mean signal levels established for performance in the range of 63-77%-Correct for a 250-Hz sinusoidal vibration to the left middle fingertip are shown in the lower panel of Fig. 1. All threshold measurements were obtained in the presence of a diotic 50 dB SPL broadband noise presented over headphones. Signal levels are plotted in dB re: 1 μm peak displacement for individual subjects who participated in each of the four experiments. Each mean level is based on 4 to 11 measurements across individual subjects and experiments. Average signal levels employed in the tactile-alone conditions ranged from -30 to -22 dB re: 1 μm peak. Within-subject values of ± 2 SEM (accounting for 96% of the measurements) ranged from 0 to 2.4 dB across subjects and experiments. The Appendix discusses the unlikely possibility that the tactile stimulus was detected auditorally via bone conduction.

The signal levels employed for the tactile-alone conditions are generally consistent with previous results in the literature for vibrotactile thresholds at 250 Hz obtained using vibrators with contactor areas similar to that of the device employed in the present study (roughly 80 mm^2). Investigators using contactor areas in the range of 28 to 150 mm^2 have reported mean thresholds in the range of -21 to -32 dB re: 1 μm peak (Verrillo, Gescheider, Calman and Van Doren, 1983; Lamore, Muijser, and Keemijik, 1986; Rabinowitz, Houtsma, Durlach and Delhorne, 1986).

B. Baseline Experiment

Results from the Baseline experiment are shown for individual subjects in Experiments 1, 2A, 2B and 2C in the four panels of Fig. 2. The mean %-Correct scores with error bars depicting ± 2 SEM are plotted for the three conditions of A-alone, T-alone, and A+T (SOA = 0 ms, Phase = 0°; see Table 1, Experimental Conditions 1-1, 2A-1, 2B-1, and 2C-1) for each subject within each experiment. Averages across subjects are provided as the rightmost data bars within each panel. Across the four experiments, there is a substantial increase in the %-Correct score when the auditory and tactile stimuli are presented simultaneously compared with the A- and T-alone conditions. Averaged over subjects, the results indicate that scores for the A-alone and T-alone condition were similar (ranging from 67.8%-74.9%-Correct across experiments) and lower than the average scores in the A+T condition (which ranged from 75.2 to 88.8%-Correct across the four experiments). Variability was generally low, with values of ± 2 SEM ranging from 0.6 to 15.1 percentage points across subjects and experiments with all but one subject less than 7 percentage points.

A 2-way ANOVA was performed on the results of the Baseline Experiment to examine the main effects of Condition (A, T, and A+ T) and Subject (11 different subjects across experiments). These results indicate a significant main effect for Condition [$F(2,257)=91.44$, $p<0.01$] but not Subject [$F(10,257)=1.00$, $p=0.035$], and a significant effect for their interaction [$F(20,257)=2.8$, $p<0.01$]. A *post hoc* analysis of the main effect of Condition showed that scores on the A+T condition were significantly greater than on the A-alone and T-alone conditions and that the A-alone and T-alone conditions were not significantly different from one another. A *post hoc* analysis of the Condition by Subject effect indicated that all subjects were similar on the A-alone and T-alone conditions but different on the A+T condition. Specifically, of the 11 subjects tested, 8 had a significantly higher A+T score compared with the A-alone and T-alone scores; two subjects showed no significant increase in score (S_8 and S_{24}); and one subject (S_{21}) had significantly greater A+T scores compared to either A-alone or T-alone, but not to both.

C. Experiment 1: Effects of Relative Auditory-Tactile Phase

The results of Experiment 1 are shown in Fig. 3. Percent-correct scores averaged across 6 subjects and 6 repetitions per condition are shown for each of the six experimental conditions: A-alone, T-alone, and combined A+T with four different values of the starting phase of the tactile stimulus relative to that of the auditory stimulus (0, 90, 180 and 270°). Average scores were 71.2%-Correct for A-alone, 72.2%-Correct for T-alone, and ranged from 83.2%- to 84.6%-Correct across the four combined A+T conditions. The Appendix discusses the unlikely possibility that this variation was caused by a bone-conducted interaction between the tactile and auditory stimuli. Variability in terms of ±2 SEM ranged from 2.0 to 2.5 percentage points across the four phase conditions.

A 2-way ANOVA was performed with main factors of Condition (A, T, A+T: tactile phase) and Subject. The results of the ANOVA indicate a significant main effect for factors of Condition [$F(5,192)=44.93$, $p<0.01$] and Subject [$F(5,192)=4.01$, $p<0.01$] but not for their interaction [$F(25,192)=1.61$, $p=0.04$]. The post hoc analysis on Condition indicated that scores on the A-alone and T-alone conditions were not significantly different from one another, that scores for the four A+T combined conditions were not significantly different from one another, and that the scores for each of the four A+T conditions were significantly greater than the A- and T-alone scores. The post hoc analysis on Subject indicated that the A+T scores for S_6 were significantly greater than those of S_1 and S_7, and that the scores for S_2 were significantly greater than those of S_7.

D. Experiment 2: Effects of Stimulus Onset Asynchrony

Experiment 2 explored the effect of stimulus onset asynchrony (SOA) between the auditory and tactile stimuli in three different experiments. Experiment 2A tested conditions in which the auditory stimulus preceded the tactile stimulus, and Experiments 2B and 2C tested conditions in which the tactile stimulus preceded the auditory stimulus. Percent-correct scores averaged across 4 subjects and 4 repetitions of each non-zero SOA condition in each of these experiments are shown in Fig. 4. Error bars represent ±2 SEM.

In Experiment 2A (Fig. 4, upper left panel), scores for the A-alone and T-alone conditions averaged 71.1%- and 71.8%-Correct, respectively. For the combined A+T conditions, average scores of the non-zero SOA conditions ranged from 71.8%-Correct (SOA = 500 ms) to 75.1%-Correct (SOA = 750 ms). Variability, in terms of ±2 SEM, ranged from 3.2 percentage points (SOA = 500 ms) to 4.3 percentage points (SOA = 700 ms). A 2-way ANOVA was conducted using main factors of Condition (A, T, and the seven combined A+T conditions with different values of SOA) and Subject. The results of the ANOVA indicate that both main factors (Condition: [$F(8,156)=6.16$, $p<0.01$]; Subject: [$F(3,156)=19.32$, $p<0.01$]), as well as their interaction [$F(24,156)=2.3$, $p<0.01$], were significant. The post hoc analysis revealed that only one A+T combined condition, that of SOA = 0 ms (i.e., the Baseline condition), produced a score that was significantly greater than the A-alone or T-alone score. The scores for the remaining SOA conditions were not significantly greater than the scores in the A-alone or T-alone conditions. The post hoc analysis of the Subject effect indicated that the scores for S_{10} were significantly different from those of the other three subjects. For the interaction effect, S_{10} showed significantly greater A+T scores at all SOA's except 750 ms compared with A- and T-alone while none of the other subjects showed a significant difference between non-zero SOA and A-alone and T-alone scores.

In Experiment 2B (Fig. 4, upper right panel), scores for the A-alone and T-alone conditions averaged 70.5%- and 73.3%-Correct, respectively. For the combined A+T conditions, averaged scores of the non-zero SOA conditions ranged from 75.7%-Correct

(SOA = -650 ms) to 82.5%-Correct (SOA = -600 ms). Variability in terms of ± 2 SEM ranged from 3.8 percentage points (SOA = -600 ms) to 6.7 points (SOA = -750 ms). The results of a 2-way ANOVA indicated that the two main effects of Condition and Subject were both significant (Condition: [$F(8,139)=6.6$, $p<0.01$]; Subject: [$F(3,139)=14.76$, $p<0.01$]), but not their interaction [$F(24,139)=1.77$, $p=0.02$]. A post hoc analysis indicated that scores on the combined A+T conditions with SOA values of 0, -500, -550, and -600 ms were significantly greater than scores on the A-alone and T-alone conditions. Scores on the combined A+T conditions with SOA values of -650, -700 and -750 ms, on the other hand, were not significantly different from A-alone and T-alone scores. A post hoc analysis of the Subject effect indicated that three of the four subjects demonstrated the main trends for Condition described above.

The results of Experiment 2C (Fig. 4, lower left panel) were similar to those found in Experiment 2B. Average scores for the A-alone and T-alone conditions were 71.9%- and 72.7%-Correct, respectively. Average scores on the combined A+T conditions ranged from 77%-Correct (SOA = -700 ms) to 81%-Correct (SOA = -600 and -750 ms). Variability in terms of ±2 SEM ranged from 4.5 percentage points (SOA = -500 ms) to 8 points (SOA = -750 ms). A 2-way ANOVA with main factors of Condition and Subject indicated significant effects for both (Condition: [$F(9,102)=10.6$, $p<0.01$]; Subject: [$F(2,102)=91.57$, $p<0.01$]), as well as for their interaction [$F(18,102)=4.69$, $p<0.01$]. A post hoc analysis of the Condition effect indicated that the scores in the combined A+T conditions for every value of SOA were significantly higher than scores on the A-alone and T-alone conditions. A post hoc analysis of the Subject effect showed that scores from all subjects tested were significantly different from one another. The response pattern for S_{10} as a function of condition differed from that of the other three subjects.

E. Comparisons to Model Predictions

Chi-Squared goodness-of-fit tests were performed in order to examine which model, the Optimal Single Channel Model (OSCM), the Pythagorean Sum Model (PSM) or the Algebraic Sum Model (ASM), best fit the measured %-Correct scores (Sec. F of Methods). The proportion of observations in agreement with predictions, i.e., having a Chi-Squared value less than 3.841, is summarized in Table 2 and also shown in Fig. 5.

The Baseline Condition (synchronous presentation, 0° tactile-auditory phase; Fig. 5 top row) was included in all testing sessions and involved 103 comparisons. Of these, 63 (61%) of the predictions agreed with the OSCM; 82 (80%) with the PSM; and 65 (63%) with the ASM. All three models failed a simple binomial test for symmetry of error.

The results of the 4 phases of Experiment 1 had similar proportions in agreement with the predictions of the PSM and ASM, indicating again that relative auditory-tactile phase had no effect on integration. The middle three panels of Fig. 5 show the predicted versus observed for all 4 phases grouped together. Out of a total of 148 observations, 96 (65%) agreed with the OSCM; 125 (85%) agreed with the PSM; and 119 (80%) agreed with the ASM. It can be seen that most of the data points that do not satisfy the Chi-Squared test are higher than the predictions of the OSCM and PSM (middle left and center panels, respectively) and lower than those of the ASM (middle right panel). The OSCM failed the symmetry test for all four phases, the PSM passed only 0 and 90°, and the ASM passed only 90°.

Discussion of the results of Experiment 2 (Stimulus Onset Asynchrony, Fig. 5, bottom row) will be restricted to non-zero SOA's because the case of zero SOA was considered above (Baseline). The bottom three panels in Fig. 5 compare observed and predicted scores in Experiment 2, segregated by sub-experiment (i.e., diamond symbols represent Experiment 2A, circles are Experiment 2B and triangles are Experiment 2C). The OSCM (lower left panel) tends to under-predict the observed scores, the PSM (lower center panel) tends to over- and under-predict to a roughly equal degree, while the ASM (lower right panel) tends to over-predict scores. Table 2 enumerates the results of Experiment 2A separately and groups the results of Experiments 2B and C together.

For Experiment 2A, the symmetry test was performed for each model and on all of the non-zero SOA values. The OSCM passed all 6 non-zero SOA values; the PSM passed all non-zero SOA values except 750 ms; and the ASM failed all non-zero SOA values. The results of a Chi-Squared test showed that the observed and predicted scores agreed 95 out of 110 times (86%) for the OSCM, and 89 (81%) for the PSM, while only 50 (45%) agreed with the ASM. Of the cases that did not pass the Chi-Squared test, the OSCM produced roughly an equal number of under- (9) and over-predictions (6), while nearly all errors were over-predictions for the PSM and ASM models.

In Experiments 2B and 2C, the OSCM passed the symmetry test for SOA values = -750, -700, and -650 ms; the PSM passed the test for all non- zero SOA values; and the ASM passed the test for only SOA = -500ms. The results of a Chi-Squared test showed that out of 202 observations (across all non-zero SOA values), 122 (60%) agreed with predictions of the OSCM, 127 (63%) with the PSM, while 124 (61%) with the ASM. However, there was a change in proportion of observations in agreement with model predictions as a function of SOA. In the case of the OSCM, for SOA values -600 or less, observations agreed with predictions 64-76% of the time, while for SOA values greater than -600 ms, this fell to less than 58% of the time. In the case of the PSM, observations agreed with predictions for all SOA values except -750 ms (all between 61% and 69%) with the lowest agreement with predictions for SOA of -750 ms (57%). In terms of the ASM, SOA values of -250, -500, -550, -600, and -650 agreed with predictions 62-67% of the time, while SOA values of -700 and -750 ms agreed 52-57% of the time.

These results could be due to within or across subject factors. Confining our attention to within subject factors, it appears that the PSM predicted the results of 4 of 11 observers in the Baseline condition and 2 of the 4 observers in Experiment 1. The OSCM and PSM each made correct predictions for 1 observer in Experiment 2A and for 2 observers each in Experiments 2B and 2C (-500 to -600 and -650 to -750 ms SOA). The ASM made no correct predictions for any subjects in Experiments 2A and 2B, and made correct predictions for 1 subject in Experiment 2C (-500 to -600 ms SOA range).

Across subjects, the PSM predicted 80% of the results in the Baseline condition, while in Experiment 1 the PSM and ASM predicted 85% and 80% of the results, respectively. For Experiment 2A, the OSCM predicted 86% of the results, the PSM 81%, and the ASM 45%. The results for Experiments 2B and 2C did not differentiate among models, each model predicting roughly 60% of the results. When applied to results from groups of observers, none of the models considered gave an accurate statistical description of all the data (i.e., greater than 95% of measurements agreeing with the predictions of a particular model). Failures to satisfy the predictions of the models are of two types: over- and under-prediction. Over-predictions relative to the OSCM accounted for only roughly 5% of the failures for the Baseline condition, Experiment 1 and 2A and only 7% for Experiments 2B and 2C. Under-predictions relative to the ASM were 2 and 5% for Experiments 1 and 2A, and 8 and 7% for the Baseline condition and Experiments 2B and 2C, respectively. The cause of the over-prediction failures may be the observer's use of the sub-optimal channel or to simple inattention. The cause of the under-prediction failures may be due to simple inattention in the single-channel presentation conditions.

IV. DISCUSSION

A. Phase and Temporal Asynchrony Effects

Our finding of phase insensitivity leads to several important interpretations regarding the facilitative effects found in the A+T conditions. First, the lack of a phase effect on the combined-modality scores strongly suggests that the auditory background noise present in all testing was sufficient to mask any possible acoustic artifacts arising from the sinusoidal vibrations produced at the tactile device. If this had not been the case, then the relative phase of the two signals would have resulted in addition and cancellation effects which would improve or decrease their detection. A second possibility that is ruled out by the present results is that of fine-structure operations at the neural level[5]. Instead, the similar A+T scores, independent of the relative phase of the auditory and tactile stimuli, suggest that the integration may operate on the envelopes of these stimuli rather than their fine structure. The response pattern measured in the current experiment is consistent with an envelope interaction effect: i.e., an overall increase in response, but no change that is correlated with changing relative auditory-tactile phase.

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[5] Although both types of interactions might occur simultaneously and cancel, we regard this possibility as unlikely.

The asymmetry in response patterns for the auditory-leading conditions compared to the tactile-leading conditions found in Experiment 2 (see Fig. 5, lower right panel) are consistent with differences in time constants between the auditory and tactile systems. The auditory-first condition suggests an integration window of no more than 50 ms while the tactile-first condition suggests a window of up to 150-200 ms.

These implications of a short auditory time constant are consistent with results obtained in studies of auditory forward masking (e.g., Robinson & Pollack, 1972; Vogten, 1977; Kidd & Feth, 1981; Jesteadt et al., 1982; Moore & Glasberg, 1983; Moore et al., 1988; Plack & Oxenham, 1997) which indicate time constants less than 50 ms. The results reported in the current study suggest that the preceding auditory stimulus was not effective in interacting with the tactile stimulus at any SOA. In the single modality case of auditory forward masking, however, there is significant interaction between the probe and masker at small time delays. The relatively long (500 ms) signal durations of both the auditory ("masker") and the tactile ("probe") stimuli may be partially responsible for the shorter auditory time constant observed here. Auditory studies typically employ brief (tens of ms) probes and strong effects have been demonstrated for an increase in the amount of forward masking with an increase in masker duration (Fastl, 1976; Kidd & Feth, 1982).

Our finding of a relatively long time constant for tactile stimulation is consistent with results obtained in studies of tactile-on-tactile forward masking (e.g., Hamer et al., 1983; Gescheider et al., 1989; Gescheider et al., 1994; Gescheider and Migel, 1995). Using tactile maskers with durations on the order of hundreds of ms and tactile probes with durations on the order of tens of ms, previous investigators have reported significant amounts of threshold shift for time delays between masker offset and probe onset on the order of 150 to 200 ms. Such results suggest that the tactile system maintains a persistent neural response even after cessation of the stimulus (see Craig & Evans, 1987). Our results are consistent with the sensory effect of the tactile stimulus persisting for at least 150 to 200 ms following its offset and that this effect is capable of interacting with the subsequent auditory stimulus to facilitate detection. For tactile offset times longer than 200 ms, the facilitatory effect declined and performance on the A+T condition was similar to that in the unimodal conditions.

B. Comparisons with Previous Multisensory Work

The facilitatory effects obtained for simultaneous presentation of A+T signals in our Baseline experiment, as well as the effects of temporal asynchrony of the auditory and tactile stimuli, are generally consistent with previous reports in the literature. Facilitative interactions for synchronously presented auditory and tactile stimuli were reported by Schnupp et al. (2005) using objective techniques to measure the discriminability of visual (V), auditory (A), and tactile (T) stimuli in VA, VT, and AT combinations. Auditory stimuli were 100 ms bursts of broadband noise presented at a background reference (sound) level of 51 dB SPL. Tactile stimuli were 100 ms bursts of 150 Hz sinusoidal vibrations presented at background reference (force) levels of 16.2-48.5 N. The stimulus on a given trial was a simultaneous pair of either VA, VT, or AT bursts that ranged from 0-14% (V and A) or 0-35% (T) in 2% or 5% increments of intensity relative to the background reference level. Observers were instructed to respond whether the background level or an incremented level was presented. Data were analyzed in terms of analogs of both the PSM and ASM. While 2 of 5 AT datasets could be adequately accounted for by the ASM (Schnupp, 2009) and 5 of 17 datasets overall, all 17 could be accounted for by the PSM.

Ro et al. (2009) measured the effect of presenting a relatively intense (59 dB) 500-Hz, 200-ms tone on the detection of a near-threshold 0.3 ms square-wave electrocutaneous stimulus that felt like a faint tap. They found that the presentation of the auditory stimulus increased d-prime from 2.4 to 2.8. This result was interpreted as evidence that "a task-irrelevant sound can enhance somatosensory perception."

Facilitative interactions have also been observed using subjective techniques such as loudness matching (Schurmann et al., 2004; Yarrow et al., 2008) and loudness magnitude estimation (Gillmeister and Eimer, 2007). In the two loudness-matching studies, the average intensity required to produce equal loudness of an auditory reference tone was 12-13% (roughly 0.5 dB) lower under the combined auditory-tactile condition compared with the auditory-alone condition, thus suggesting a facilitative interaction between the auditory and tactile stimuli. Gillmeister and Eimer (2007) found that magnitude estimates of an auditory tone presented in a background of white noise were increased by simultaneous presentation of a tactile stimulus for near-threshold auditory tones, but no loudness increase was observed either for higher intensity tones or for non-simultaneous presentation of the tactile and auditory stimuli. It should be noted, however, that based on the results of other experiments, Yarrow et al. (2008) attribute the increase in loudness to a bias effect. They conclude that the tactile stimulus "does not affect auditory judgments in the same manner as a real tone."

Other previous studies of auditory-tactile integration have measured effects of temporal asynchrony between the two stimuli and have also demonstrated dependence on the order of stimulus presentation: Gescheider and Niblette (1967) for inter-sensory masking and temporal-order judgments and Bresciani et al. (2005) for judgments of auditory numerosity. Consistent with the results of the current study, higher levels of interaction between the two senses were obtained for conditions in which the tactile stimulus is delivered before the auditory stimulus. One exception to this pattern is found in the results of Gillmeister and Eimer (2007). While demonstrating effects of temporal synchrony on the detectability of an auditory tone in the presence of a vibratory pulse, they found no effects of stimulus order. Their detectability results, however, are consistent with the results of their loudness-estimation study.

While the experimental conditions used in these studies differ from one another, they all suggest that temporal synchrony is an important factor in showing facilitative auditory-tactile interaction. The current study has shown in greater detail the asymmetry in the temporal window involved in auditory-tactile detection, such that when the tactile stimulus precedes the auditory by up to 200 ms, a facilitative interaction significantly greater than the unimodal levels is measured. This level of response is not seen when the auditory stimulus precedes the tactile, however, as bimodal responses at all asynchronous time periods are not different from unimodal levels.

C. Implications of Model Results

We quantified the amount of integration measured in this study by comparing performance with the predictions of three models of the integration process: The Optimal Single Channel Model (OSCM), the Pythagorean Sum Model (PSM) and the Algebraic Sum Model (ASM). It should be noted that these models are not mutually exclusive in the sense that observers need not base their decisions exclusively on one model in all experiments. If the auditory stimulus is presented before the tactile, it is unlikely that the ASM would apply, while it might apply when there is temporal overlap. Also, the predictions of more than one model may fit the data equally well. For example, in the hypothetical case considered in Methods, Section F, based on 75 trials the score of 75%-Correct would be within two standard deviations of the predictions of all three models. Many of the two-frequency results of Marill (1956) can be accounted for by two of these three models. It is only possible to distinguish among the three models based on more than one experimental result, i.e., several results from one observer or the results of multiple observers. When performance exceeds the predictions of the OSCM, this implies at least partial integration of cues and when performance exceeds predictions of the PSM, this implies at least partial within-channel integration.

In this study, the results show that measurements are more often successfully modeled by the Pythagorean Sum approach than by the Optimum Single Channel or Algebraic Sum approaches and are consistent with those found previously in auditory alone studies (Green, 1958), tactile alone studies (Bensmaia et al., 2005) and in multisensory studies (audio-visual and audio-visual-tactile: Braida, 1991; visual-tactile: Ernst & Banks, 2002; discrimination of pairs of visual-auditory, visual-tactile, and audio-tactile stimuli: Schnupp et al., 2005). Although most of these studies did not attempt to model the observations with an Algebraic Sum model, Schnupp et al. (2009) found that 2 of 5 Audio-Tactile discrimination datasets could be fit by an ASM (all 5 were fit by a PSM) and we found in Experiment 1 that nearly the same number of experiments were accounted for by the ASM as by the PSM.

Thus we found, in accord with Schnupp et al. (2005), that overall the PSM best accounts for the improvement in detectability when auditory and tactile stimuli are combined. There are significant differences, however: the OSCM provides a slightly better account when auditory stimuli precede tactile stimuli and the ASM provides nearly as good an account of the (non-)effects of varying relative auditory-tactile phase. One problem with this interpretation is that the different models make predictions of detectability that are always ordered: OSCM $\leq$ PSM $\leq$ ASM. Thus, for example, if an observer behaves in accord with the ASM, but makes a few responses due to inattention, the PSM will tend to be favored. While we discarded data sets for which there were indications that unimodal observer detection had decreased during the course of single session, it is likely that some reduction in bimodal detection may have occurred as well. Because Schnupp et al. (2005) collected data over two or three sessions, it is also possible that criterion shifts may have reduced apparent performance, thus favoring the PSM over the ASM.

It is also possible that the PSM provides a better description of the data than the ASM when qualitatively different stimuli are detected or discriminated. The traditional explanation for the two-frequency detection results of Marill (1956) and Green (1958) is that the PSM provides a good account of the detection of pairs of tones whose frequencies lie in distinct critical bands while the ASM is appropriate for tones whose frequencies lie in the same critical band. Wilson et al. (2008), who tested the detection of auditory and tactile tones of varying frequency, found that performance generally declined as the frequency difference increased. It is possible that Schnupp et al. (2005)

found that a PSM like model applied to discrimination of auditory noise and a tactile tone for this reason.

Stein and Meredith (1993) have suggested that additive and super-additive responses are a way of measuring facilitative multisensory responses. The different models suggest different mechanisms for integration, with the Pythagorean Sum modeling two independent pathways integrating the different stimuli after each has been processed by its own sensory system and the Algebraic Sum modeling stimuli that are integrated before being processed, leading to a greater level of integration overall. It is possible that both the results of Schnupp et al. (2005) and our results, which show that subjects can utilize both Pythagorean and Algebraic approaches to integration, suggest that the auditory and tactile sensory systems are capable of integrating in both manners, and both mechanisms are being employed during our experiment.

D. Relationship to NeuroAnatomy

One potential anatomical pathway for Pythagorean integration may be the ascending somatosensory inputs to the somatosensory cortex which then project to the auditory cortex. Thus, two independent pathways are operating on input from each of the modalities and the multisensory stimuli are processed only after the single-modality operations have taken place. A different anatomical pathway that may account for Algebraic integration comes from the ascending somatosensory inputs that target early auditory centers (i.e., in the brainstem and thalamus) and thereby affect changes in auditory-tactile integration before the combined signal reaches the auditory cortex. The fact that we see observed responses that are greater than the prediction of Pythagorean

Sum model suggests that the auditory and somatosensory systems are working together in one multisensory area to process the stimuli.

V. CONCLUDING REMARKS

Our study has shown that certain combinations of auditory and tactile signals result in a significant increase in detectability above the levels when the stimuli were presented in isolation. This is not due to changes in response bias (e.g., Yarrow et al., 2008), as indicated by a detection theory analysis. Specifically, we have shown significant increases in detectability that are independent of relative auditory-tactile phase when the auditory and tactile stimuli are presented simultaneously, suggesting that the envelopes, and not the fine structure, of the two signals interact in a facilitative manner. Additionally, we have also shown asymmetric changes in detectability when the two signals are presented with temporal asynchrony: when the auditory signal is presented first, detectability is not significantly greater than in A-alone or T-alone conditions, but when the tactile signal is presented first, detectability is significantly greater for almost all values of SOA employed. These differences are consistent with the neural mechanics of auditory-on-auditory masking and tactile-on-tactile masking.

Our results were compared with three models of integration. While it is not always possible to differentiate among the models on the basis of a single experimental outcome, the models sort themselves out if one combines results across sessions and/or observers. If one assumes that all observers use a single model in all experiments, then the Pythagorean Sum Model gives a better fit to the data than the Optimal Single Channel Model or the Algebraic Sum Model.

Further research is being conducted to examine the effects of other stimulus parameters (including frequency and intensity) on the perceptual aspects of auditory-tactile integration.

VI. ACKNOWLEDGMENTS

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APPENDIX: ESTIMATIONS OF BONE-CONDUCTED SOUND LEVELS ARISING FROM VIBROTACTILE STIMULATION AT 250 HZ

We consider two possibilities and show that they are unlikely to be responsible for our results: 1) in Baseline conditions the vibratory stimulus is detected through the auditory sense; and 2) in Experiment 1, the phase dependent combination of vibratory and acoustic stimuli is responsible for the phase dependence of our results. Note that masking noise was used in an attempt to ensure that the task is performed solely through the sense of touch without spurious auditory cues.

Consider first the possibility that bone-conducted sound from vibratory stimulation was responsible for detection of the tactile stimulus. In the measurements of Dirks et al. (1976), bone-conduction thresholds for normal listeners in force and acceleration units, indicate that the 250-Hz bone-conduction threshold, when measured with a vibrator placed on the mastoid, is 10 dB re 1 cm/sec^2 (acceleration units). The maximum displacement of our 250-Hz signal (roughly 5 dB SL) corresponds to a peak displacement of -20 dB re 1 μmeter peak and an acceleration of roughly 5 dB re 1 cm/sec^2, roughly 5 dB less than the bone-conduction threshold for mastoid stimulation. It is fairly safe to assume that stimulation of the index finger results in a highly attenuated bone-conducted signal compared to stimulation of the mastoid. The bone-conducted threshold at the forehead is 12 dB higher than at the mastoid. The impedance mismatches created by tissue and bone junctions from the fingertip to the skull would lead to even higher thresholds, perhaps by 13 dB, than for the forehead. Thus the highest signal reaching the ear through bone-conducted sound at 250 Hz would be -20 dB re 1 cm/sec^2. The bone-conducted threshold at 250-Hz is 10 dB cm/sec^2; thus our bone-conducted stimulus would be roughly -30 dB SL, that is, roughly 30 dB below the air-conducted threshold of 18 dB SPL at 250 Hz (Houtsma, 2003) or equivalent to an acoustic stimulus of –12 dB SPL. Such bone-conducted sound would be undetectable.

Assuming a critical ratio of 17.5 dB at 250 Hz and a noise spectral level of 7.4 dB/Hz, the level of the acoustic tone is roughly 25 dB SPL, and (as noted above) the equivalent vibratory stimulus is –12 dB SPL, 37 dB below the level of the acoustic tone. This would cause the 25 dB SPL tone to vary at most from 24.9 to 25.1 dB SPL as the phase is changed. To understand the effect of this phase change, we make use of some unpublished data on the detection of auditory stimuli of different amplitudes: 25 dB and 27 dB, which correspond to detection rates in the 50 dB SPL noise of 70.9% and 79.9% respectively, or about 4.5 percentage points per dB. Thus the combination of the bone- and the air-conducted sound would cause the detection rate to change from 70.3 to 71.5%. This is contrary to the results of Experiment 1, which indicate that in the A+T condition in scores varied between 83.2 and 84.6% with standard errors of less than 1.3 percentage points. This indicates that the effect of combining the vibratory and acoustic stimuli cannot be accounted for by bone conduction alone.

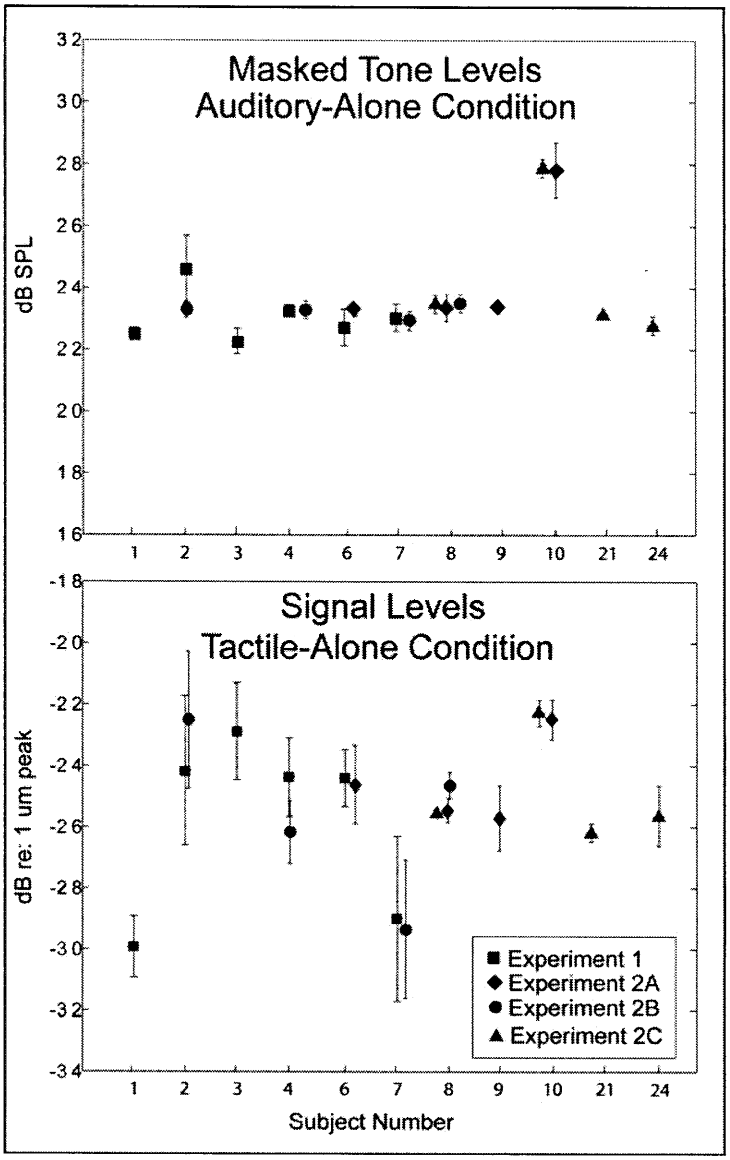

Figure 1: Single-modality signal levels employed for individual subjects tested in each of the four experiments. Auditory levels are for detection of a 250-Hz pure tone in 50–dB SPL broadband noise. Tactile levels are for detection of a 250-Hz sinusoidal vibration presented to the fingertip. Different symbols represent results obtained in different experiments. Some subjects participated in more than one experiment. Error bars are 2 SEM.

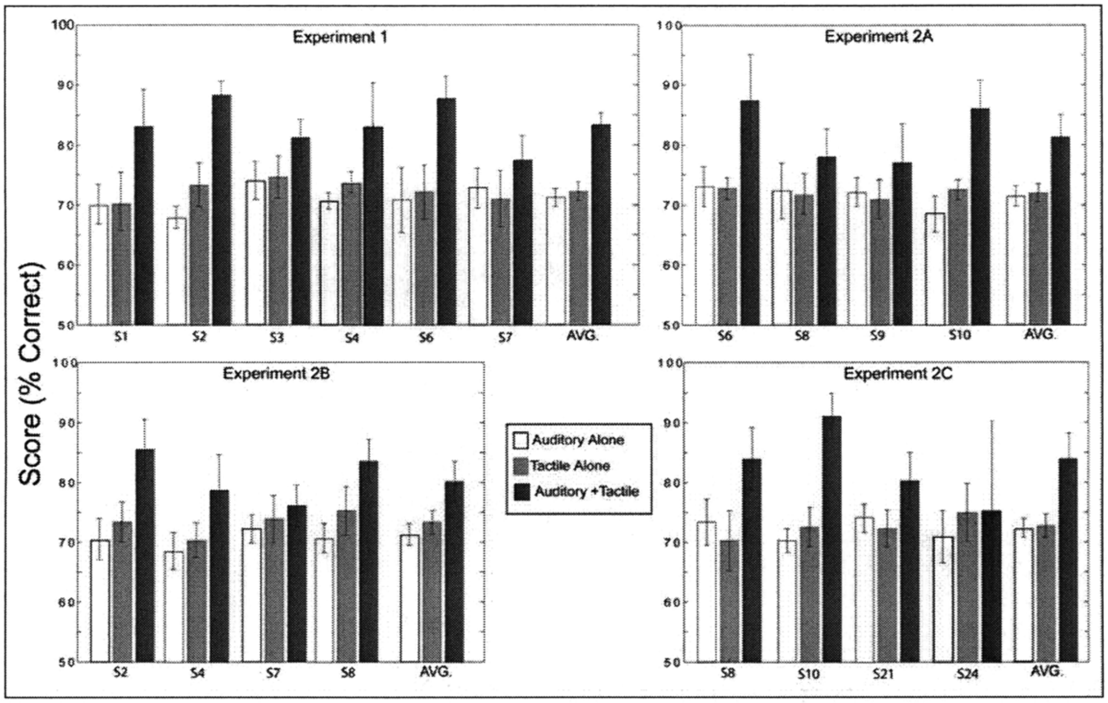

Figure 2: Summary of results for Baseline Condition in Experiments 1, 2A, 2B, and 2C. %-Correct scores for the individual subjects in each experiment are averaged across multiple repetitions per condition; number of repetitions varies by subject, and is equal to or greater than 4 per subject. AVG is an average across subjects and repetition in each experiment. White bars represent Auditory-alone conditions, grey bars represent Tactile-alone conditions, and black bars represent the A+T Baseline condition with SOA = 0ms and phase = 0°. Error bars are two SEM.

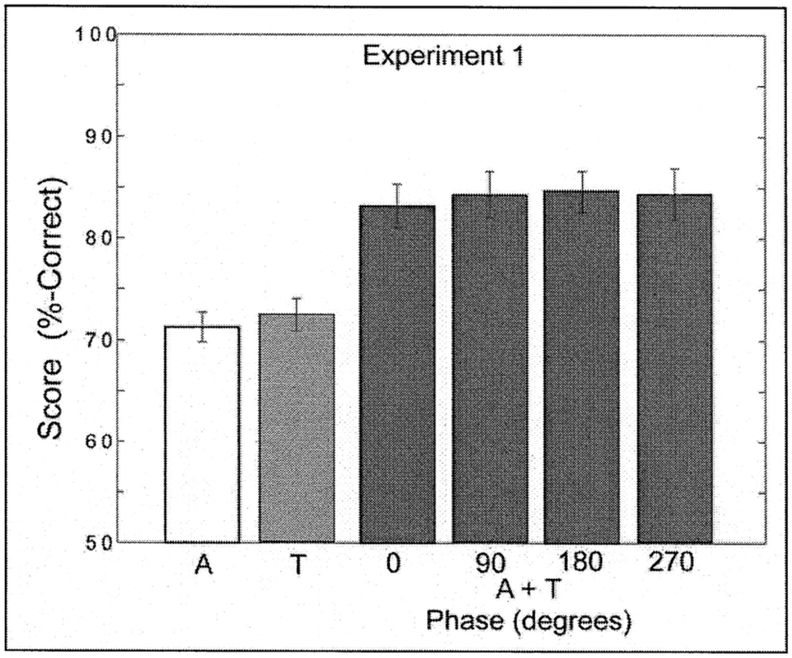

Figure 3: Summary of results for Experiment 1. %-Correct scores are averaged across 6 subjects with 6 sessions per condition. Scores are shown for A-alone (white bar), T-alone (light grey bar) and for combined A+T condition (dark grey bars) as a function of starting phase (in degrees) of the tactile stimulus relative to the auditory stimulus. Error bars are two SEM.

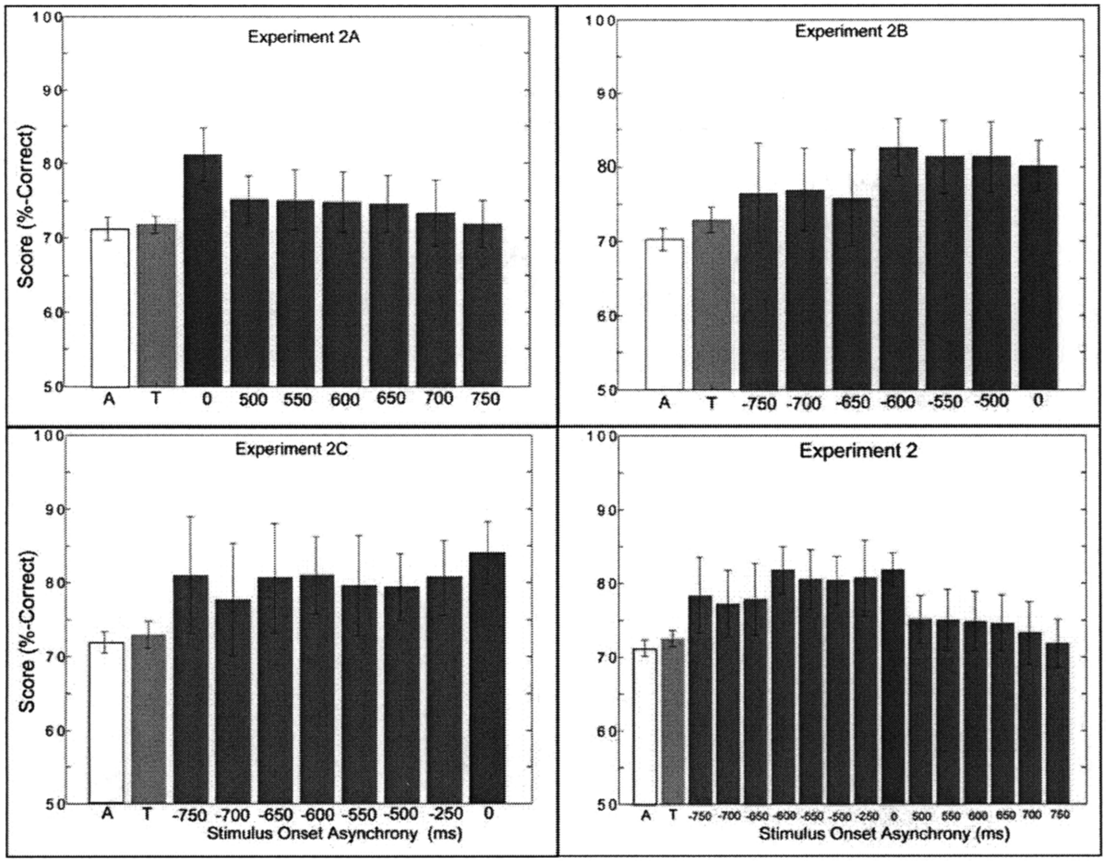

Figure 4: Summary of results for Experiment 2. In all panels, scores are shown for A-alone (white bars), T-alone (light grey bars) and combined A+T condition (dark grey bars). In the upper left panel, (Experiment 2A: Auditory Precedes Tactile), %-Correct scores are averaged across 4 subjects with 4 sessions per condition (SOA = 0 ms has more than 4 repetitions). In the upper right panel, (Experiment 2B: Tactile Precedes Auditory), %-Correct scores are averaged across 4 subjects with 4 sessions per condition (SOA = 0 ms has more than 4 repetitions). In the lower left panel, (Experiment 2C: Tactile Precedes Auditory, with temporal overlap), %-Correct scores are averaged across 4 subjects with 4 sessions per condition (SOA = 0 ms has more than 4 repetitions). The lower right panel (Experiment 2) provides a composite summary of %-Correct scores averaged across all subjects and repetitions from Experiments 2A, 2B and 2C. In all panels, error bars are two SEM.

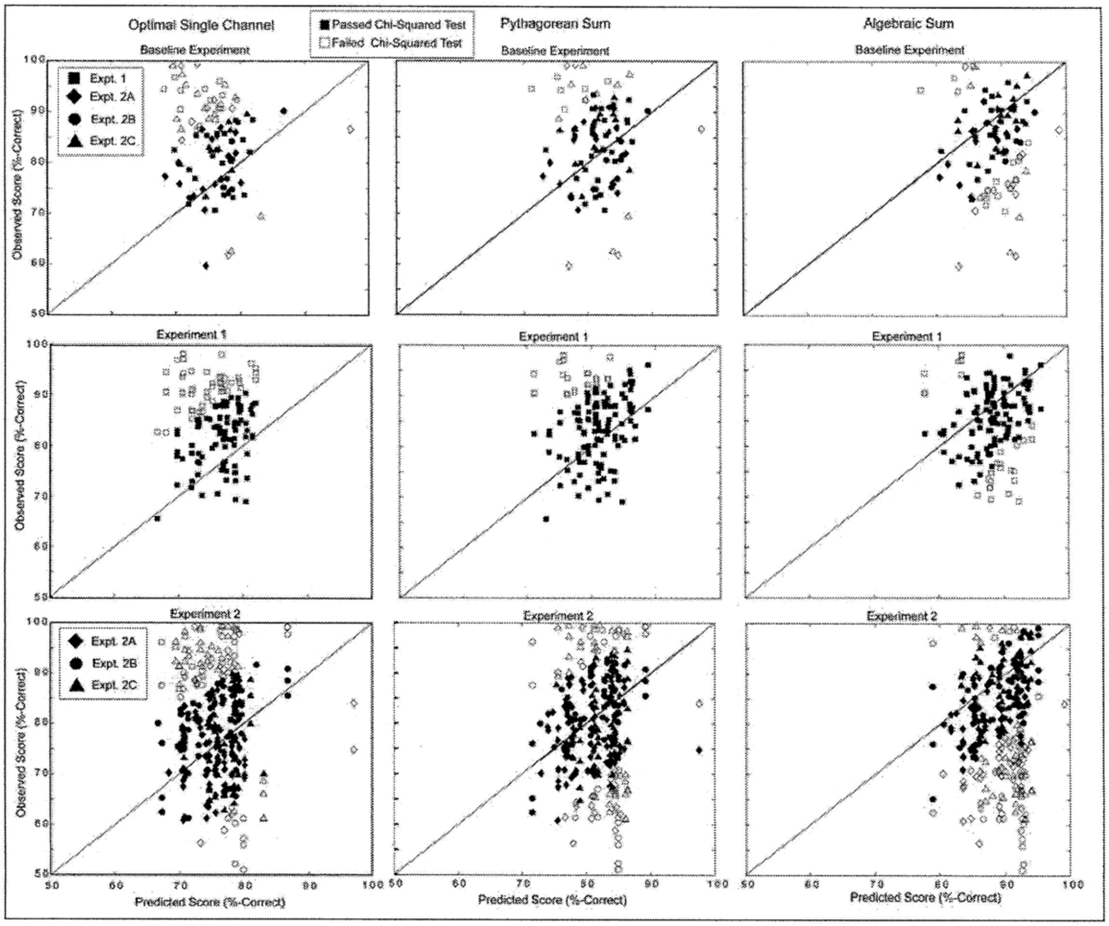

Figure 5: Predicted vs. Observed values for the three models of integration: Optimal Single Channel Model (far left column), Pythagorean Sum (middle column) and Algebraic Sum (right column). The first row shows all values from the Baseline Experiment (SOA = 0, Phase = 0°); data from each experiment are designated by a different shape (see legend). The second row shows values from all phases in Experiment 1 (Relative Phase). The third row shows all non-zero SOA values from Experiment 2; each sub-experiment delineated by shape (see legend). Open symbols indicate that the observed value failed the Chi-Squared test and filled symbols indicate the observed value passed the Chi-Squared test.

Table I. Description of experimental conditions studied in Experiments 1, 2A, 2B and 2C. In all experiments, the frequency of the auditory and tactile stimulus was always 250 Hz with duration of 500 ms. Stimulus onset asynchrony (SOA) was defined as SOA = Onset Time$_{\text{Tactile}}$ – Onset Time$_{\text{Auditory}}$.

Experiment 1: Variable Studied: *Phase*					
Condition	**Starting Phase (degrees)**		**SOA (msec)**	**Subjects**	**# Repetitions**
	Auditory Stimulus	Tactile Stimulus			
1-1	0	0	0	S_1,S_2,S_3,S_4,S_6,S_7	6
1-2	0	90	0	S_1,S_2,S_3,S_4,S_6,S_7	6
1-3	0	180	0	S_1,S_2,S_3,S_4,S_6,S_7	6
1-4	0	270	0	S_1,S_2,S_3,S_4,S_6,S_7	6
Experiment 2: Variable Studied: *Stimulus Onset Asynchrony* **Experiment 2A: Auditory Stimulus Precedes Tactile Stimulus**					
2A-1	0	0	0	S_6,S_8,S_9,S_{10}	≥ 4

2A-2	0	0	500	S_6,S_8,S_9,S_{10}	4
2A-3	0	0	550	S_6,S_8,S_9,S_{10}	4
2A-4	0	0	600	S_6,S_8,S_9,S_{10}	4
2A-5	0	0	650	S_6,S_8,S_9,S_{10}	4
2A-6	0	0	700	S_6,S_8,S_9,S_{10}	4
2A-7	0	0	750	S_6,S_8,S_9,S_{10}	4
Experiment 2: Variable Studied: *Stimulus Onset Asynchrony* **Experiment 2B: Tactile Stimulus Precedes Auditory Stimulus, no temporal overlap**					
2B-1	0	0	0	S_2,S_4,S_7,S_8	≥ 4
2B-2	0	0	-500	S_2,S_4,S_7,S_8	4
2B-3	0	0	-550	S_2,S_4,S_7,S_8	4
2B-4	0	0	-600	S_2,S_4,S_7,S_8	4
2B-5	0	0	-650	S_2,S_4,S_7,S_8	4
2B-6	0	0	-700	S_2,S_4,S_7,S_8	4
2B-7	0	0	-750	S_2,S_4,S_7,S_8	4

Experiment 2: Variable Studied: *Stimulus Onset Asynchrony*

Experiment 2C: Tactile Stimulus Precedes Auditory Stimulus, with temporal overlap condition

2C-1	0	0	0	S_8,S_{10},S_{21},S_{24}	≥ 4
2C-2	0	0	-250	S_8,S_{10},S_{21},S_{24}	4
2C-3	0	0	-500	S_8,S_{10},S_{21},S_{24}	4
2C-4	0	0	-550	S_8,S_{10},S_{21},S_{24}	4
2C-5	0	0	-600	S_8,S_{10},S_{21},S_{24}	4
2C-6	0	0	-650	S_8,S_{10},S_{21},S_{24}	4
2C-7	0	0	-700	S_8,S_{10},S_{21},S_{24}	4
2C-8	0	0	-750	S_8,S_{10},S_{21},S_{24}	4

Table II. Chi-Squared Tests: Predicted vs. Observed. This table enumerates the number of observations that have passed/failed the Chi-Squared goodness of fit test for each of the three models (i.e., Optimal Single Channel, Pythagorean Sum and Algebraic Sum).

Experiment	***Condition***	***Total***	***Optimal Single Channel***			***Pythagorean Sum***			***Algebraic Sum***		
			Pass	***Fail***	***Under predict Fail***	***Pass***	***Fail***	***Under predict Fail***	***Pass***	***Fail***	***Under predict Fail***
	Baseline										
1	Phase = 0°	40	26	14	14	33	7	7	27	13	3
2A	SOA = 0 ms	26	17	9	7	20	6	3	14	12	2
2B & C	SOA = 0 ms	37	20	17	15	29	8	6	24	13	3
Totals		*103*	*63* *(61%)*	*40*	*36* *(35%)*	*82* *(80%)*	*21*	*16* *(16%)*	*65* *(63%)*	*38*	*8* *(8%)*
	Phase										
1	0°	40	26	14	14	33	7	7	27	13	3
1	90°	36	24	12	12	29	7	7	31	5	2
1	180°	37	25	12	12	33	4	4	29	8	1
1	270°	35	21	14	14	30	5	5	32	3	2
Totals		*148*	*96* *(65%)*	*52*	*52* *(35%)*	*125* *(84%)*	*24*	*23* *(16%)*	*119* *(80%)*	*29*	*7* *(5%)*
	SOA										
2A	500 ms	19	18	1	1	18	1	1	10	9	1
2A	550 ms	18	15	3	3	15	3		9	9	
2A	600 ms	19	15	4	1	15	4		10	9	
2A	650 ms	18	17	1	1	15	3	1	7	11	1
2A	700 ms	18	14	4	2	11	7		8	10	
2A	750 ms	18	16	2	1	15	3		6	12	
Totals		110	95 (86%)	15	9 (8%)	89 (81%)	21	2 (2%)	50 (45%)	60	2 (2%)

	SOA										
2B & C	-250 ms	17	13	4	4	11	6	3	11	6	2
2B & C	-500 ms	33	20	13	12	21	12	9	22	11	2
2B & C	-550 ms	31	21	10	9	19	12	7	19	12	3
2B & C	-600 ms	36	23	13	12	25	11	7	23	13	4
2B & C	-650 ms	28	16	12	8	17	11	6	18	10	1
2B & C	-700 ms	29	14	15	11	18	11	4	15	14	1
2B & C	-750 ms	28	15	13	9	16	12	6	16	12	2
Totals		*202*	*122* *(60%)*	*80*	*65* *(32%)*	*127* *(63%)*	*75*	*42* *(21%)*	*124* *(61%)*	*78*	*15* *(7%)*

Chapter 3. Effects of Frequency Between the Auditory and Vibrotactile Stimuli

The work described in this chapter has been submitted to the Journal of the Acoustical Society of America as "Integration of auditory and vibrotactile stimuli: effects of frequency"

ABSTRACT

Perceptual integration of vibrotactile and auditory sinusoidal tone pulses was studied in detection experiments as a function of stimulation frequency. Vibrotactile stimuli were delivered through a single-channel vibrator to the left middle fingertip. Auditory stimuli were presented diotically through headphones in a background of 50-dB-SPL broadband noise. Detection performance for combined auditory-tactile presentations was measured using stimulus levels that yielded 63%-77%-correct unimodal performance. In Experiment 1, the vibrotactile stimulus was 250 Hz and the auditory stimulus varied between 125-2000 Hz. In Experiment 2, the auditory stimulus was 250 Hz and the tactile stimulus varied between 50-400 Hz. In Experiment 3, the auditory and tactile stimuli were always equal in frequency and ranged from 50-400 Hz. The highest rates of detection for the combined-modality stimulus were obtained when stimulating frequencies in the two modalities were equal or closely spaced (and were within the Pacinian range). Combined-modality detection for closely-spaced frequencies was generally consistent with an Algebraic-Sum model of perceptual integration, while wider-frequency spacings were generally better fit by a Pythagorean-Sum model. Thus, perceptual integration of auditory and tactile stimuli at near-threshold levels appears to depend both on absolute frequency and relative frequency of stimulation within each modality.

I. INTRODUCTION

Recent anatomical and neurophysiological research has shown evidence of interaction between the auditory and somatosensory systems at various levels of the central nervous system in both animals (e.g., Zhou and Shore, 2004; Cappe and Barone, 2005; Schroeder et al., 2001) and in humans (Foxe et al., 2002; Schurmann et al., 2006). Perceptual studies also provide evidence for auditory-somatosensory interactions. For example, facilitative interactions between auditory and touch have been observed using subjective techniques such as loudness matching (e.g., Schurmann et al., 2004; Yarrow et al., 2008; Gillmeister and Eimer, 2007) as well as objective measurements of detection and discrimination (e.g., Schnupp et al., 2005; Wilson et al., 2009; Yau et al., 2009; Ro et al., 2009).

Our previous research in this area (Wilson et al., 2009) examined the perceptual integration of auditory and vibrotactile 250-Hz tones in an objective detection task as a function of the relative phase and temporal asynchrony of 500-ms tone pulses. Our results indicated that performance increased significantly over unimodal detection when the auditory and tactile signals were presented synchronously, and that the combined performance increase was not affected by the relative phase between the auditory and tactile stimuli. The lack of a phase effect suggests an envelope rather than a fine-structure operation for integration. The effects of presenting the auditory and tactile stimuli with no temporal overlap (i.e., asynchronously) were consistent with time constants deduced from single-modality masking experiments. For example, when the tactile signal preceded the auditory signal, a significant increase in performance was observed for temporal separations up to 100 ms between the offset of the tactile stimulus and the onset of the auditory stimulus. On the other hand, when the auditory stimulus was presented before the tactile stimulus (with no temporal overlap), performance on the combined condition was not significantly different from performance on either the auditory- or tactile-alone conditions.

The current study extends our previous work by examining the effects of stimulus frequency on auditory-tactile integration when stimuli in both modalities are presented simultaneously at signal levels near the threshold of detection. Given that both of these sensory systems respond differentially to frequency (auditory: Fletcher and Wegel, 1922; Dadson and King, 1952; Watson et al., 1972; Fletcher, 1940; Schreiner et al., 2000; Romani and Williamson, 1981; Bilecen et al., 1998; Talavage et al., 2000; Talavage et al., 2004; somatosensory: Gescheider et al., 2002; Bolanowski et al., 1988; Gescheider et al., 2001; Harris et al., 2006; Hegner et al., 2007; Francis et al., 2000; Harrington and Downs, 200; Iguchi et al., 2007) and that the frequency region to which both systems are responsive is limited, it is possible that frequency of stimulation may be an important variable in auditory-tactile perceptual interactions. Specifically, we hypothesize that if the auditory and tactile systems integrate into a common neural pathway, then interaction effects should be greater than when they integrate in different pathways. Furthermore if the same frequency is conveyed by a common pathway and different frequencies are conveyed by different pathways, then integration effects should be greater when both modalities are stimulated by the same frequency than by different frequencies.

This paper explores the frequency relationship between audition and touch in a signal detection task in three experiments. In Experiment 1, the frequency of the auditory component assumed values in the range of 125 to 2000 Hz while the frequency of the tactile component was held constant at 250 Hz. In Experiment 2, the frequency of the tactile signal assumed values in the range of 50 to 400 Hz while the frequency of the auditory component was held constant at 250 Hz. In Experiment 3, the frequencies of the auditory and tactile stimuli were equal to each other and assumed values in the range of 50 to 400 Hz. For comparison purposes, we tested purely auditory detection with a 250-Hz narrowband noise that was combined with tones of frequency ranging from 125-2000 Hz (Appendix). These experiments were designed (a) to test the effects of frequency separation between the auditory and tactile components on multisensory integration and (b) to test the effects of frequency of stimulation when the auditory and tactile stimulating frequencies were equal to one another and co-varying. Measurements of d' (and %-correct) were obtained for auditory-alone, tactile-alone, and combined auditory-tactile presentations. The observed performance in the combined condition was then compared to predictions of multi-modal performance derived from observed measures of detectability within each of the two separate sensory modalities.

In our previous work, the observed multi-modal data were compared to three different models of predicting auditory-tactile scores based on unimodal scores. These models included the Optimal Single Channel Model (OSCM), the Pythagorean Sum Model (PSM), and the Algebraic Sum Model (ASM). The OSCM assumes that the observers' responses are based on the better of the tactile or auditory input channels; the PSM assumes that integration occurs across channels (e.g., as in audio-visual integration, Braida, 1991) and that the combined auditory-tactile response is the Pythagorean sum of the separate channels; and the ASM assumes that integration occurs within a given channel and that the combined response is the linear sum of the scores for the separate channels. On average, the observed scores tended to be greater than the prediction of the OSCM and the PSM but less than the prediction of the ASM. The same models of integration were applied in the current research to determine the manner in which properties of integration are affected by frequency of stimulation in each modality.

II. METHODS

C. Stimuli and Block Diagram

The auditory stimuli were pure tones presented in a background of pulsed 50-dB SPL Gaussian broadband noise (bandwidth of 0.02 to 11.0 kHz). The frequency of the auditory stimulus across the three experiments was 50, 125, 250, 400, 500, 1000 and 2000. The tactile stimuli were sinusoidal vibrations with a frequency of 50, 125, 250 and 400 Hz across the three experiments. The background noise was used to mask possible auditory cues arising from the tactile device and was present in all auditory (A), tactile (T), and combined auditory plus tactile (A+T) test conditions. Sinusoidal signals in both modalities were generated digitally (using Matlab 7.1 software) to have a total duration of 500 ms that included 20-ms raised cosine-squared rise/fall times.

The digitized signals were played through a D/A sound card (Lynx Studio Lynx One) with a sampling frequency of 24 kHz and 24-bit resolution. The auditory signal was sent through channel 1 of the sound card to a programmable attenuator (TDT PA4) and headphone buffer (TDT HB6) before being presented diotically through headphones (Sennheiser HD 580). The tactile signal was passed through channel 2 of the sound card to a programmable attenuator (TDT PA4) and amplifier (Crown D-75) before being delivered to an electromagnetic vibrator (Alpha-M Corporation model A V-6). The subject's left middle fingertip made contact with the vibrator (0.9 cm diameter) which was housed inside a wooden box for visual shielding and sound attenuation. A heating pad was placed inside the box to keep the box and tactile device at a constant temperature. A laser accelerometer was used to calibrate the tactile device so that displacement could be measured from input voltage.

D. Subjects

Eight subjects ranging in age from 18 to 45 years (four females) participated in this study. Audiological testing was conducted on the first visit to the laboratory. Only those subjects who met the criterion of normal audiometric thresholds (20 dB HL or better at frequencies of 125, 250, 500, 1000, 2000, 4000 and 8000 Hz) were included in the studies. All subjects were paid an hourly wage for their participation in the experiments and signed an informed-consent document prior to entry into the study. Five subjects participated in Experiment 1 (S_1, S_6, S_{10}, S_{13}, and S_{14}), four in Experiment 2 (S_1, S_6, S_{10}, and S_{11}), and four in Experiment 3 (S_6, S_{10}, S_{18}, and S_{22}). Three of the subjects participated in multiple experiments (S_1: Experiments 1 and 2, S_6 and S_{10}: Experiments 1, 2 and 3). These three subjects also participated in experiments conducted by Wilson et al., (2009) and subject identification is consistent with that used in our previous paper.

C. Experimental Conditions

The experiments examined the perceptual integration of sinusoidal auditory and vibrotactile signals with different values of frequency, which were presented near the threshold of detection. Threshold measurements were first obtained under each of the two single-modality conditions (A and T separately). Then the detectability of the combined A+T signal was measured at levels established for threshold within each of the two individual modalities. The experimental conditions examined the effects of frequency under different relative conditions: Auditory frequency varied, tactile frequency constant (Experiment 1); tactile frequency varied, auditory frequency constant (Experiment 2); and auditory and tactile frequency equal and co-varied (Experiment 3).

A summary of the audio-tactile conditions employed in the three experiments is provided in Table I. For all A+T conditions, the auditory and tactile sinusoids were presented in sinusoidal phase with equal onset and offset times. The stimulus parameters are described in terms of the frequency of the auditory (column 2) and tactile (column 3) stimuli. Information concerning the subjects and the number of repetitions of each experimental condition is provided in the final two columns of Table I.

Baseline Condition. A baseline condition employing an equal frequency of 250 Hz for both A and T stimulation was included in each of the experiments (Conditions 1-2, 2-3, and 3-3 in Table I).[6]

Experiment 1 examined the effect of varying the frequency of the auditory stimulus while holding the tactile stimulus frequency constant and is described in Table I (Conditions 1-1 through 1-5). The frequency of the tactile stimulus was held constant at 250 Hz while the frequency of the auditory stimulus took on five different values: 125, 250, 500, 1000, and 2000 Hz. The order of the five experimental A+T conditions was randomized for each of six replications for each of the five subjects. Subjects required a total of five days (S_6) to twelve days (S_1) of testing to complete the experiment.

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[6] For subjects who participated in more than one experiment (S_1, S_6 and S_{10}), this Baseline condition was not repeated for each experiment. For S_1, the Baseline condition was measured in Experiment 1 only and the same data were used for Experiment 2 (Condition 2-3). For S_6, the Baseline condition was measured in Experiment 1; for Experiments 2 and 3 the Baseline data used measurements for this subject taken previously by Wilson et al. (2009). For Subject S_{10}, the Baseline condition was measured for Experiments 1 and 3; for Experiment 2, Baseline data were taken from measurements made previously by Wilson et al., (2009).

Experiment 2 examined the effect of varying the frequency of the tactile stimulus while holding the auditory stimulus frequency constant and is described in Table I (Conditions 2-1 through 2-4). The frequency of the auditory stimulus was held constant at 250 Hz while the frequency of the tactile stimulus took on four different values: 50, 125, 250, and 400 Hz. The order of the four experimental A+T conditions was randomized for each of four replications for each of the four subjects. One subject (S_{11}) required six days to complete the repetitions of the four combined runs, while the remaining three subjects (S_1, S_6, and S_{10}) required ten days.

Experiment 3 examined the effect of co-varying the frequencies of both the tactile and auditory stimulus while holding them equal to one another and is described in Table I (Conditions 3-1 through 3-4). The frequencies of the auditory and tactile stimuli were 50, 125, 250, and 400 Hz. The order of the four experimental A+T conditions was randomized for each of four replications for each of the four subjects. Two subjects (S_{10} and S_{22}) required nine total days, while S_6 and S_{18} required eleven and twelve days of testing, respectively, to complete the experiment.

D. Experimental Procedures

For all experimental conditions, subjects were seated in a sound-treated booth and were presented 50 dB SPL broadband noise diotically via headphones. For testing in conditions that involved presentation of the tactile stimulus (T and A+T), the subject placed the left middle finger on the electromagnetic vibrator. In each experimental session, testing was first conducted for A-alone and T-alone separately to establish a signal level for single-modality performance in the range of 63-77%-correct. Performance was then measured in the A+T conditions for a given experiment. The number of experimental A+T conditions that could be completed within a given test session was generally dependent on the time required to establish signal levels that met the single-modality performance criterion. Each experimental session lasted no more than two hours on any given day and subjects were required to take frequent breaks throughout the session. For each subject, three training sessions identical to the experimental sessions were provided before data were recorded.[7]

In Experiments 1 and 2, certain single-modality conditions were re-tested in the fixed-level procedure before the end of each session to ensure that thresholds remained stable throughout the session. For Experiment 1, only T-alone was re-tested and for Experiment 2, only A-alone was re-tested. No post-session test was performed for Experiment 3 because the thresholds were measured immediately preceding each combined run. If single-modality thresholds were less than 56%-correct or greater than 84%-correct (± 2 standard deviations assuming an original score of 70%-correct), the data for that session were discarded. If a subject's threshold shifted more than 2 standard deviations in three non-training sessions, our policy was to terminate that subject from the study; however, all subjects met the qualification for threshold stability and none were disqualified on these grounds.

2-Interval, 2-Alternative Forced Choice (2-I, 2-AFC) Tests. The threshold estimates under the single-modality A and T conditions employed a 2-I, 2-AFC fixed-level procedure with 75 trials per run. Stimulus levels were adjusted and runs were repeated until scores of 63-77%-correct were obtained. These stimulus levels were then used in testing the combined A+T conditions with the fixed-level 2-I, 2-AFC procedure.

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[7] Subjects S_1, S_6, and S_{10} participated in an earlier study (Wilson et al., 2009) and received their three training sessions at that time in the Baseline experiment.

On each presentation, the stimulus (A, T, or A+T) was presented with equal *a priori* probability in one of the two intervals. The interval duration was 1.1 seconds for all experiments. Each observation interval was marked by a visual cue that appeared on a computer terminal located in front of the subject. Noise was presented diotically over headphones starting 500 ms before the first interval, and played continuously throughout a trial (including the durations of the two intervals and the 500-ms duration between intervals) before being turned off 500 ms after the end of the second interval. Each trial had a fixed duration of 3.7 seconds, plus the time it took subjects to respond. The onset of the stimulus (A, T, or combined A+T) was always coincident with the onset of the observation interval in which it appeared. Subjects responded between trials by selecting the interval in which they thought the stimulus was presented (using either a mouse or keyboard) and were provided with visual correct-answer feedback after each trial. Attention to the combined A+T stimulus was encouraged by having subjects count the number of times they perceived a signal.

E. Data Analysis

A two-by-two stimulus-response confusion matrix was constructed for each 75-trial experimental run, and was used to determine percent-correct scores and signal-detection measures of sensitivity (d'). These measures were averaged across the repetitions of each experimental condition within a given subject. Statistical tests performed on the data included ANOVAs on the arcsine transformed percent-correct scores, with statistical significance level defined for probability (p-values) less than or equal to 0.01. For statistically significant effects a *post hoc* Tukey-Kramer analysis was performed with alpha = 0.05.

F. Models of Integration

The results of the experiments were compared with three different models of integration: The Optimal Single Channel Model (OSCM), the Pythagorean-Sum Model (PSM), and the Algebraic-Sum Model (ASM). The OSCM assumes that the observers' responses are based on the better of the tactile or auditory input channels. The predicted D'_{OSCM}[8] for the combined A+T condition is the greater of the tactile (d'_T) or auditory (d'_A), $D'_{OSCM} = \mathrm{Max}(d'_T, d'_A)$. The PSM assumes that integration occurs across channels (e.g., as in audio-visual integration, Braida, 1991) and that the d' in the combined auditory-tactile condition is the Pythagorean sum of the d-prime's for the separate channels, $D'_{PSM} = \sqrt{d'_A{}^2 + d'_T{}^2}$. The ASM, on the other hand, assumes that integration occurs within a given channel and that the combined d' is the linear sum of the d-prime's for the separate channels, $D'_{ASM} = d'_A + d'_T$. For example, if the auditory d'_A was 1.0 (69%-correct) and the tactile d'_T was 0.8 (66%-correct), the OSCM would predict a D'_{ASM} of 1.0 (69%-correct), the PSM would predict a D'_{PSM} of 1.28 (74%-correct) and the ASM would predict a D'_{ASM} of 1.8 (82%-correct). The OSCM prediction is never greater than the PSM prediction, which in turn is never greater than the prediction of the ASM.

Chi-Squared goodness-of-fit calculations were employed to compare observed with predicted values from each of the three models. The predictions of the models were evaluated as follows: First, d-prime's were determined for each auditory (d'_A) and tactile (d'_T) experiment, on the basis of 75 total trials. Second, predicted d-prime's were computed for the three models according to the formulas given above. Third, predicted %-correct scores were computed for each of the models in the following manner: %-

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[8] We denote d-primes that can be estimated directly from the data using lower case (d'), and d-primes that are predicted by models by upper case letters (D').

correct = $100\phi(\frac{D'_{A+T}}{2})$, where ϕ is the cumulative of the Gaussian distribution function, and D'_{A+T} is the predicted D'. Fourth, the observed A+T confusion matrix was analyzed to estimate d'_{A+T} and the "no bias" estimate of %-correct score was computed as $\%_{A+T}$ = $100\phi(\frac{d'_{A+T}}{2})$. This relatively small adjustment (1.6 percentage points on average, 13 points maximum) was necessary because the predictions of the models assumed that the observer is not biased. Predictions (D'_{OSCM}, D'_{PSM}, and D'_{ASM} or $\%_{OSCM}$, $\%_{PSM}$ and $\%_{ASM}$) were compared with observations (d'_{A+T} or $\%_{A+T}$). The proportion of the observations that agreed with predictions was judged by having a Chi-Squared value less than 3.841 (the 95% criterion) between predicted and observed scores (corrected as discussed above) using a contingency table analysis (Neville and Kennedy, 1964). This analysis allows for errors in both the observed score and the predicted score.

III. RESULTS

C. Signal Levels Employed in Single-Modality Conditions

Levels for Auditory-Alone Conditions. The mean signal levels that yielded performance in the range of 63% to 77%-correct for auditory pure tones in 50-dB SPL broadband noise are shown in the upper panel of Fig. 1. Frequencies measured in these experiments included 50, 125, 250, 400, 500, 1000, and 2000 Hz. Mean levels are plotted for each individual subject for the frequencies tested in each of the three experiments. Each data point depicted in the plot is based on an average of at least 4 and as many as 11 measurements per frequency. Averaged across subjects and experiments, the mean threshold level for each of the tones is shown as a solid line. Within a given subject, levels for all frequencies tested were highly stable for measurements made within a given experiment and across experiments. For all but one subject, values of ± 2 standard error of the mean (SEM; accounting for 96% of the measurements) ranged from 0.0 to 1.92 dB across subjects and experiments. For that subject (S_{10}), variability was slightly higher (2.77 dB) in the 400-Hz condition in Experiment 3.

Critical ratios (CR) were calculated for the tone-in-noise levels shown in Fig. 1 by subtracting the spectrum level of the noise from the presentation levels of the different tones employed in these experiments. The spectrum level was flat from approximately 100 Hz to 11 kHz (7.4 dB/Hz) but was 20 dB/Hz at 50 Hz. The magnitude of the CR was consistent with the values reported by Hawkins and Stevens (1950) in the range of 125 to 2000 Hz, and with values reported by Houtsma (2004) for 50-Hz tones. These results indicate that subjects were listening to tones at levels near masked threshold.

Levels for Tactile-Alone Conditions. The mean signal levels that yielded performance in the range of 63% to 77%-correct for a sinusoidal vibration (50, 125, 250, and 400 Hz) to the left middle fingertip are shown in the lower panel of Fig. 1. All threshold measurements were obtained in the presence of a diotic 50 dB SPL broadband noise presented over headphones. Mean levels are shown for individual subjects who participated in each of the three experiments. Each data point is based on 4 to 20 measurements per frequency across individual subjects and experiments. The average level across subjects is represented by the solid line in the lower panel of Fig. 1. Within-subject values of ± 2 SEM (accounting for 96% of the measurements) ranged from 0 to 2.2 dB across subjects and experiments.

Mean thresholds measured across the three experiments were 1.0 dB re: 1 μm peak at 50 Hz, -21.7 dB at 125 Hz, -24.2 dB at 250 Hz, and -14.6 dB at 400 Hz. These threshold values are consistent with previous measurements using contactor areas in the range of 28 to 150 mm^2 (e.g., Gescheider, et al. 2002; Verrillo, et al., 1983; Lamore, et al., 1986; Rabinowitz, et al., 1986; Verrillo, 1963) and show a similar frequency dependence. Specifically, maximal sensitivity is obtained at 250 Hz and thresholds increase at frequencies above and below this value.

D. Baseline Experiment

Results from the Baseline experiment are shown for individual subjects in Experiments 1, 2, and 3 in the three panels of Fig. 2 (2a, 2b, and 2c, respectively). The mean %-correct scores with error bars depicting ± 1 SEM are plotted for the three conditions of A-alone, T-alone, and A+T (Auditory and Tactile frequency = 250 Hz; see Table I, Experimental Conditions 1-2, 2-3, and 3-3) for each subject within each experiment. Averages across subjects are provided as the rightmost data bars within each panel. For each of the three experiments, there is a substantial increase in the %-correct score for the A+T condition compared with the A-alone and T-alone conditions. The mean scores on each condition, averaged over subjects, were similar across experiments: A-alone values were 70.5, 71.5, and 72.9%-correct (Experiments 1, 2, and 3, respectively); T-alone values were 70.9, 72.6, and 74.3%-correct (Experiments 1, 2, and 3, respectively); and A+T values were 86.6, 86.3, and 87.9%-correct (Experiments 1, 2, and 3, respectively). Variability on the combined A+T condition was generally low, with values of ± 2 SEM ranging from 2.8 to 7.0 percentage points across subjects and experiments. These results are consistent with values previously reported by Wilson et al. (2009) for the Baseline experiment.

A two-way ANOVA was performed on the arcsine transformed percent-correct scores of the Baseline experiment to examine the main effects of Condition (A, T, A+T) and Subject (8 different subjects across experiments). The results indicate a significant main effect for Condition [$F(2,111)=88.5$, $p<0.01$] but not for Subject [$F(7,111)=2.09$, $p = 0.05$] or for their interaction [$F(14,111)=1.99$, $p=0.025$]. A *post hoc* analysis of the main effect of Condition showed that scores on the A+T condition were significantly greater than on the A-alone and T-alone conditions and that the A-alone and T-alone conditions were not significantly different from one another.

C. Experiment 1: Auditory Frequency Varied, Tactile Frequency Constant

The results of Experiment 1 are shown in Fig. 3(a). Percent-correct scores averaged across five subjects and four repetitions per condition are shown for each of the five experimental conditions: A-alone, T-alone, and combined A+T with five different values for the frequency of the auditory tone (125, 250, 500, 1000 and 2000 Hz) while the frequency of the tactile tone remained constant at 250 Hz. The average score for T-alone was 70.9%-correct. The average score for A-alone ranged from 69.1%-correct (2000 Hz) to 72.3%-correct (125 Hz). Variability in terms of ± 2 SEM was small and ranged from 1.3 (A = 2000 Hz) to 2.3 (A = 1000 Hz) percentage points across all single-modality conditions. Average scores for the A+T conditions changed as a function of auditory stimulus frequency. The highest score of 86.6%-correct was obtained with A = 250 Hz. The A+T conditions with other auditory frequencies resulted in lower scores: 125 Hz = 82.5%-correct; 500 Hz = 82.0%-correct; 1000 Hz = 77.5%-correct; and 2000 Hz = 80.6%-correct. Variability was small, with ± 2 SEM values ranging from 2.9 (A = 125 Hz) to 5.0 (A = 1000 Hz) percentage points.

For each of the five values of auditory frequency, a separate two-way ANOVA was performed with main factors of Condition (A, T, and A+T) and Subject. The results of each of the five ANOVAs indicated a significant main effect for the factor of Condition: 125 Hz [$F(2,45)=34.24$, $p<0.01$]; 250 Hz [$F(2,45)=61.84$, $p<0.01$]; 500 Hz [$F(2,45)=29.52$, $p<0.01$]; 1000 Hz [$F(2,45)=11.72$, $p<0.01$]; and 2000 Hz [$F(2,45)=48.12$, $p<0.01$]. A significant effect of Subject was observed in only two cases: 1000 Hz [$F(4,45)=4.89$, $p<0.01$] and 2000 Hz [$F(4,45)=5.95$, $p<0.01$]. The *post hoc* analyses on Condition for each auditory frequency value indicated that scores on the A-alone and T-alone conditions were not significantly different from one another but that the score for the combined A+T conditions was significantly higher than the single-modality scores. The *post hoc* analysis on Subject for the 1000-Hz condition indicated that the A+T score for S_{10} was significantly higher than scores for S_{13}, S_{14} and S_6. For the 2000-Hz condition, the *post hoc* analysis on Subject indicated that the A+T score for S_{10} was significantly higher than the A+T scores of S_1, S_{14} and S_6 but not of S_{13} and that subjects S_{14} and S_6 did not show any significant increase in A+T over single modality scores.

An additional two-way ANOVA was conducted on the five combined A+T scores only and indicated a significant effect for Condition [$F(4,75)=5.094$, $p<0.01$] and Subject [$F(4,75)=18.02$, $p<0.01$] but not for their interaction [$F(16,75)=2.13$, $p=0.015$]. The post-hoc analysis on Condition showed an auditory-frequency specific trend such that the A+T score on the 250-Hz condition was significantly higher than the A+T scores for the 1000- and 2000-Hz conditions, but not for the 125- and 500-Hz conditions. The scores for the 125-, 500-, 1000- and 2000-Hz conditions were not significantly different from one another. The *post hoc* analysis on Subject indicated that the A+T scores were ordered as follows: $S_{10} > S_1, S_6 > S_{13}, S_{14}$.

D. Experiment 2: Tactile Frequency Varied, Auditory Frequency Constant

The results of Experiment 2 are shown in Fig. 3(b). Percent-correct scores averaged across four subjects and four repetitions per condition are shown for each of the four experimental conditions: A-alone, T-alone, and combined A+T with constant auditory stimulus frequency (250 Hz) and four different values of the tactile stimulus frequency (50, 125, 250 and 400 Hz). The average score for A-alone was 71.3%-correct. T-alone scores ranged from 69.8%-correct (at T = 50 Hz) to 73.4%-correct (at T = 250 Hz). Variability in terms of ± 2 SEM was small and ranged from 1.6 (A = 250 Hz) to 2.4 (T = 250 Hz) percentage points across all single-modality conditions. Average scores for the A+T conditions changed as a function of tactile stimulus frequency. The highest score of 86.4%-correct was obtained with a tactile frequency of 250 Hz. Lower scores were obtained with other tactile frequencies: 50 Hz = 76.2%-correct; 125 Hz = 85.8%-correct; and 400 Hz = 78.8%-correct. Variability was small, with ± 2 SEM values ranging from 2.1 (T = 250 Hz) to 4.4 (T = 400 Hz) percentage points.

For each of the four values of tactile frequency, a separate two-way ANOVA was performed on the arcsine transformed percent-correct scores with main factors of Condition (A, T, A+T) and Subject. The results of the ANOVAs indicate a significant main effect for Condition with tactile frequencies of 125 Hz [F(2,36)=44.01, $p<0.01$], 250 Hz [F(2,36)= 47.92, $p<0.01$], and 400 Hz [F(2,36)=10.99, $p<0.01$]. A significant Subject effect was obtained only at 125 Hz [F(2,36) = 5.32, $p<0.01$], where the interaction of Subject and Condition was also significant [F(2,36)= 5.25, $p<0.01$]. The *post hoc* analyses on Condition indicated that scores on the A-alone and T-alone conditions were not significantly different from one another at each of the four tactile frequency values. For tactile frequencies 125, 250, and 400 Hz, scores for the A+T condition were significantly higher than the A-alone and T-alone scores. For the 50 Hz condition, the combined A+T score was significantly higher than the T-alone but not the A-alone score. The *post hoc* analysis on the Subject effect for the 125-Hz condition indicated that the A+T score for S_{10} was significantly higher than those for S_1, S_{11} and S_6.

An additional 2-way ANOVA was performed on the four A+T percent-correct scores only and indicated a significant effect for Condition [F(3,48) = 26.34, $p < 0.01$], no effect for Subject [F(3,48) = 3.3, $p = 0.028$], and a significant effect for their interaction [F(9,48) = 2.96, $p < 0.01$]. A *post hoc* analysis on Condition showed that the scores on the 125- and 250-Hz tactile conditions were not significantly different from one another, but were significantly higher than the scores for T = 50 and 400 Hz. The *post hoc* analysis on subject showed that scores for S_1 were significantly less than those of S_{10}.

E. Experiment 3: Auditory and Tactile Frequency Equal and Co-Varied

The results of Experiment 3 are shown in Fig. 3(c). Percent-correct scores averaged across four subjects and four repetitions per condition are shown for each of the four experimental conditions: A-alone, T-alone, and combined A+T with four different values of frequency where A=T (50, 125, 250 and 400 Hz). Average scores for A-alone ranged from 70.5%-correct (at 125 Hz) to 72.5%-correct (at 50 and 250 Hz) and the T-alone scores ranged from 70.6%-correct (at 50 Hz) to 74.1%-correct (at 250 Hz). Variability in terms of ± 2 SEM was small and ranged from 1.9 (A=50 Hz) to 2.4 (T=50 Hz) percentage points across all single-modality conditions. Average scores for the A+T conditions were 78.3%, 86.47%, 87.25% and 85.8%-correct for auditory-tactile frequencies of 50, 125, 250 and 400 Hz, respectively. Variability was smallest on the 250-Hz condition, with a ± 2 SEM value of 2.8 percentage points, while that of other frequencies ranged from 5.0 (125 Hz) to 5.6 (50 Hz) percentage points.

A separate two-way ANOVA was performed on the arcsine transformed percent-correct scores for each value of frequency with main factors of Condition (A, T, A+T) and Subject. The results of the ANOVAs indicated a significant main effect for Condition at each of the four frequencies: 50 Hz [F(2,36)=10.73, $p<0.01$]; 125 Hz [F(2,36)=47.01, $p<0.01$]; 250 Hz [F(2,36)=35.19, $p<0.01$]; and 400 Hz [F(2,36)=48.1, $p<0.01$]). There was a significant effect of Subject for frequencies of 50 Hz [F(2,36)=7.76, $p<0.01$], 125 Hz [F(2,36)=8.01, $p<0.01$], and 400 Hz [F(2,36)=5.8, $p<0.01$]. The interaction of Subject and Condition was also significant for frequencies of 125 Hz [F(6,36)=7.99, $p<0.01$] and 400 Hz [F(6,36)=8.25, $p<0.01$]. The *post hoc* analysis on Condition indicated that scores on the A-alone and T-alone conditions were not significantly different from one another and that the scores for the combined A+T conditions were significantly higher than both A-alone and T-alone. The *post hoc* analysis on Subject showed that the scores of S_{22} were significantly less than those of S_{10} (in the 50 and 125 Hz conditions) and were also significantly less than those of S_6 (in the 400 Hz condition).

An additional two-way ANOVA was performed on the four combined A+T conditions only and indicated that there was a significant effect of Condition [F(3,49)=4.98, $p<0.01$], Subject [F(3,49)=11.79, $p<0.01$], and their interaction [F(9,49)=4.73, $p<0.01$]. A *post hoc* analysis on Condition showed that the 50-Hz A+T score was significantly less than the A+T scores for 125, 250 and 400 Hz (which were not significantly different from one another) and the *post hoc* analysis on Subject showed that scores for S_{10} were significantly higher than those of S_6, S_{18} and S_{22}. The interaction effect possibly stems from the fact that scores for subjects S_6 and S_{22} were significantly less on the 50-Hz condition compared with S_{18} and S_{10}, and that S_{22} showed significant increase in performance for the 250-Hz condition only.

F. Comparisons to Model Predictions

Chi-Squared goodness-of-fit tests were performed on the data in order to examine which model, the Optimal Single Channel Model (OSCM), the Pythagorean Sum Model (PSM), or the Algebraic Sum Model (ASM), best fit the measured percent-correct scores (Sec. II-F). The proportion of observations in agreement with predictions, i.e., having a Chi-Squared value less than 3.841, is summarized in Table 2. Figures 4(a) and 4(b) show plots of the observed versus predicted percent-correct scores for PSM and ASM, respectively, on the Baseline conditions from each experiment. Figures 4(c) and 4(d) show plots of the observed versus predicted percent-correct scores for PSM and ASM, respectively, for the data set from Experiment 3 (auditory and tactile frequencies equal and co-varied). These conditions were chosen because they represent an extension of the baseline data from Wilson et al. (2009) and because they demonstrate the best fits to the PSM and ASM models. The remaining conditions (i.e., in which the frequency of the auditory and tactile stimuli were different from one another) are summarized in Table II, but not displayed. In Figs. 5(a), 5(b), and 5(c), the ratio of observed d-prime to predicted D-prime is plotted as a function of stimulus frequency for each of the three experiments (Experiments 1, 2 and 3, respectively).

The Baseline Condition [equal auditory-tactile frequency of 250 Hz; Figs. 4(a) and 4(b)] was included in all experiments and involved a total of 53 comparisons. Of these, 30 (57%) agreed with OSCM predictions; 40 (76%) agreed with PSM predictions; and 46 (87%) agreed with ASM predictions. All of the OSCM and PSM prediction failures are due to under-prediction while the ASM under-predicted only 2 out of 7 failures. It can be seen that most of the data points that do not satisfy the Chi-Squared test are higher than the predictions of the PSM (Fig. 4(a)) and lower than the predictions of the ASM (Fig. 4(b)), consistent with results found previously in Wilson et al. (2009). Of the 8 subjects tested, 2 (S_{13} and S_{18}) had more than 95% of measurements passing the Chi-Squared test for the PSM, while 2 had more than 95% of measurements passing the Chi-Squared test for the ASM (S_{11} and S_{18}). The "extended baseline" condition will be discussed below in the context of results from Experiment 3.

The results of Experiment 1 indicated a change in best-model fit as a function of auditory frequency. When the auditory and tactile frequencies were equal (250 Hz, Baseline condition), the ASM model (81%) outperformed the PSM and OSCM (67% and 52%, respectively). When the auditory and tactile stimuli were not equal in frequency, however, the PSM outperformed the ASM and OSCM by 4-18 percentage points. The largest prediction difference between models was measured at 125 Hz, and the three models predicted observations almost equally well at 2000 Hz (resulting in the smallest prediction difference). The OSCM did not accurately model any conditions of Experiment 1 (between 50% and 68% of observations passing the prediction criterion). Even though the 2000-Hz condition had the same percentage of observations passing the model prediction using the OSCM and ASM (55%), all of the failures of the OSCM were under-predictions, while only 30% of the failures of the ASM were under-predictions. Figure 5(a) shows that the ratio of observed d-prime to predicted D-prime values was close to 1 for the ASM when the auditory frequency was 250 and 2000 Hz, and close to 1 for the PSM when the auditory frequency was 1000 Hz. For the 125- and 500-Hz conditions, the ratios fell between the PSM and ASM predictions.

For Experiment 2, a frequency-dependent trend was also observed. When the tactile frequency was 125 or 250 Hz, the ASM model best fit the observations (88% and 94% passing the Chi-Squared tests, respectively). In the 50-Hz tactile frequency condition, both the OSCM and PSM best fit the observations (94% passing the Chi-Squared test in each model). Similarly, in the 400-Hz tactile frequency condition, both the OSCM and PSM fit the observations equally well (75% passing Chi-Squared tests in each model). Again, the same trend occurred such that the OSCM and PSM tended to under-predict the observations, while the ASM tended to over-predict observations. Figure 5(b) shows that the ratio of observed d-prime to predicted D-prime values is consistent with the percentages passing the Chi-Squared test. Tactile frequency conditions of 125 and 250 Hz were best predicted by the ASM (with ratios close to 1) while conditions in which the tactile frequency was equal to 50 or 400 Hz were best predicted by the OSCM or PSM, respectively.

For Experiment 3, in which the auditory and tactile frequencies were equal and co-varied, the ASM best fit the observations for the 125- and 250-Hz conditions, with 57% and 88% passing the Chi-Squared tests, respectively. In the 125-Hz condition, 5 out of 7 of the failures are due to ASM under-prediction. In the 50-Hz condition, the PSM best fit the data with 94% of observations passing the Chi-Squared test, with no under-predictions for either PSM or ASM. In the 400-Hz condition, each model scored the same percentage of observations passing the chi-squared test (63%). However, all three models under-predicted the observations and of the 6 ASM failures, 3 are due to model under-prediction. Figure 5(c) shows a similar trend such that the ASM was most accurate in predicting the observations when the auditory and tactile frequencies were equal to 125, 250, and 400 Hz, but that the PSM was the most accurate in predicting the observations when the stimulus frequencies were equal to 50 Hz.

IV. DISCUSSION

A. Effects of frequency separation

Effects of the frequency of stimulation on auditory-tactile integration of signals presented at near-threshold levels were observed in each of the three experiments. Such effects were present both for signal detectability (as measured in percent-correct scores) of the combined A+T stimulus and for best fits to different models of integration. Generally, a tendency was observed for higher rates of detection of the combined-modality stimulus when the stimulating frequencies in the two modalities were equal or close to one another, and for lower rates of detection as the frequency separation of the auditory and tactile stimuli increased. Furthermore, the ASM (indicative of within-channel integration) provided a better fit to the data when the auditory and tactile stimulating frequencies were equal or close to one another compared to a better fit of the PSM (indicative of cross-channel integration) for larger frequency spacings. Measurements of the detectability of purely auditory stimulus pairs (Appendix) gave similar results to our measurements of auditory-tactile stimuli, with the exception of the

(125, 250) Hz condition. Apparently the auditory separation, roughly 3 ERB (Moore et al., 1990), is effectively greater than the tactile separation.

A Baseline condition employing 250-Hz stimulation in both auditory and tactile modalities was included in each of the three experiments, as it was in Wilson et al. (2009). The results of this condition, which are in good agreement with those reported by Wilson et al. (2009), indicate a roughly 15 percentage-point increase in the percent-correct score for A+T compared with A-alone or T-alone. On average, A+T performance on the Baseline condition was well-modeled by the within-channel integration process of the ASM.

The Baseline measurement was extended in Experiment 3 where the auditory and tactile stimulating frequencies were set equal to one another but took on values of 50, 125, and 400 Hz in addition to the original baseline value of 250 Hz. The results of this experiment indicate detection rates of the A+T stimulus at 125 and 400 Hz that are equivalent to those at 250 Hz (i.e., roughly 86%-correct) and that are well-modeled by the within-channel model of integration (ASM). At the 50-Hz frequency, however, average performance on the A+T condition (78%-correct) was lower than for the remaining three frequencies and was best-modeled by the cross-channel model of integration (PSM), with only 2 of the 4 subjects showing ASM-type integration. Whereas the three higher frequencies (125, 250, and 400 Hz) are well-within the range of the Pacinian receptor system (Verrillo, 1963; Hamer et al., 1983), at 50-Hz it is likely that the non-Pacinian and Pacinian receptors may also convey aspects of the tactile stimulus: the non-Pacinian receptors respond robustly for frequencies less than 50 Hz ("flutter") and Pacinian receptors respond robustly for frequencies greater than 50 Hz ("vibration").

The significant subject effect observed at 50 Hz may be indicative of differences in tactile physiology among subjects. In fact, the observation that two of the four subjects (S_{10} and S_{18}) showed sizable A+T scores (> 85%-correct) when both frequencies were equal to 50 Hz while two others (S_6 and S_{22}) did not, suggests that the cross-over point between the non-Pacinian and Pacinian receptors may be different across individuals. Those subjects with high A+T scores at 50 Hz may have a cross-over point lower in frequency than those subjects whose A+T scores at 50 Hz were similar to single-modality scores. Additional data collected on subject S_6 at 60 and 75 Hz corroborates this claim: at 50 and 60 Hz, responses to the combined A+T stimulus were approximately 77%-correct, but at 75 Hz, combined responses were approximately 90%-correct. This result suggests a cross-over frequency between non-Pacinian and Pacinian receptors somewhere in the range of 60-75 Hz for this subject.

When different auditory frequencies were combined with a 250-Hz tactile signal (Experiment 1), A+T scores were similar for auditory values of 125, 500, 1000, and 2000 Hz and, on average, were lower than that obtained for the equal-frequency 250-Hz auditory condition. For the non-equal frequency conditions (with the exception of 2000 Hz), multi-modal performance was over-predicted by the PSM but under-predicted by the ASM, whereas the ASM provided an excellent fit to the Baseline condition. Unexpectedly, average performance for the condition with an auditory frequency of 2000 Hz was also well-modeled by the ASM. Individual-subject differences were observed on this condition, indicating that the results of one subject (S_{14}) were well-modeled by the OCSM while that of two other subjects (S_1 and S_{10}) were well-modeled by the ASM. No obvious explanation for these inter-subject differences is apparent.

When different tactile stimulating frequencies were combined with an auditory frequency of 250 Hz (Experiment 2), integration of the two stimuli was similar for tactile frequencies of 125 and 250 Hz (indicating within-channel integration predicted by the ASM) but was less effective for tactile frequencies of 50 and 400 Hz. The integration effects with a 400-Hz tactile signal were fairly well-modeled with the PSM whereas those with a 50-Hz signal were closer to the OSCM. In comparing the results of Experiments 1 and 2, one can conclude that the filtering in Experiment 1 is similar to auditory critical-band filtering whereas a broader tactile filter is implied by the results of Experiment 2.

B. Comparisons with previous studies

Other perceptual studies have explored the frequency relationship between the auditory and tactile stimuli through "roughness judgments." For example, the "parchment-skin illusion" (Jousmaki and Hari, 1998; Guest et al., 2002) demonstrates that the percept of tactile roughness can be modulated by manipulating the high frequency components of the auditory signal. The attenuation of high frequencies results in a "less rough" percept of the tactile stimuli compared to no manipulation, whereas the amplification of high-frequency components leads to a percept of greater roughness compared to the baseline condition.

Two recent perceptual studies have reported effects of frequency on auditory-tactile interactions in tactile frequency-discrimination tasks performed in the presence of auditory "distracter" tones (Ro et al., 2009; Yau et al., 2009). Ro et al. (2009) examined the ability to discriminate between 100-Hz and 200-Hz vibratory stimuli using a 1-I, 2AFC procedure for stimulus presentations that included tactile stimulation alone and tactile stimulation in conjunction with a synchronous auditory tone of 100 or 200 Hz.

The tactile stimuli were 250-msec in duration and were presented at levels that were subjectively matched to produce a "moderately intense percept" through a piezoelectric element at the dorsal surface of the left hand. The auditory stimuli, which were also 250-msec in duration, were presented through a loudspeaker located in front of the subject's left hand at a level of roughly 60 dB SPL. The mean hit rates were 0.62 for the tactile-alone stimulus presentations, 0.74 for presentations with equal-frequency auditory and tactile tones, and 0.43 for presentations with different-frequency auditory and tactile tones. Thus, performance was aided by the presence of auditory tones matched in frequency to the tactile sinusoids but declined in the presence of incongruous auditory tones. In fact, performance appears to be substantially worse than that expected on the basis of chance alone for the incongruous conditions. For the 200-Hz tactile, 100-Hz auditory condition, the hit rate was only 0.37, suggesting that subjects were able to discriminate the stimuli but reversed their corresponding response labels of "high" and "low". Thus, the 100-Hz auditory tone appears to have lowered the perception of the higher-frequency tactile signal..

Yau et al. (2009) used a 2I, 2AFC procedure to measure frequency discrimination for 1-s sinusoidal tactile signals presented to the right index finger. For a 200-Hz standard tactile stimulus (delivered over a contactor with 1-mm diameter), tactile comparison stimuli were seven sinusoids that were equally spaced in frequency over the range of 100-300 Hz and whose levels were equated for perceived intensity with the 200-Hz standard (whose level was 11.2 μm). On most trials of the experiment, an auditory tone (one of 8 values in the range of 100-1500 Hz with individual-tone levels in the range of 56.5-76.4 dB SPL selected to be equated for loudness) was presented synchronously with the comparison stimulus. (Although absolute thresholds for the tactile and auditory stimuli were not reported in this study, it is reasonable to assume that all signals were substantially above threshold—see discussion of tactile thresholds in Sec. III-A of the current paper.) The remaining trials, conducted without the auditory "distracter" tones, were used to establish baseline performance for the tactile frequency-discrimination task. The psychometric functions showed a significant reduction in sensitivity (i.e., ΔF for 73%-correct performance) compared to baseline performance only for those auditory distracters that were less than or equal to 300 Hz and a significant change in bias (i.e., the point of perceived subjective equality) for auditory distracters of 100 Hz only. An analogous frequency-discrimination experiment conducted with a 400-Hz tactile standard stimulus (delivered over a contactor with 8-mm diameter at a level of 1 μm) indicated a significant reduction in sensitivity for auditory distracters in the range of 100-400 Hz and changes in bias for auditory tones of 100-300 Hz. Thus, these results suggest a significant interaction between auditory and tactile stimuli that are similar in frequency in performing a tactile frequency-discrimination task. No such effects of the frequency of auditory distracter tones were observed, however, in a tactile intensity-discrimination task employing either a 100-Hz standard (at a level of14.2 μm and comparisons in the range of 7.1-21.4 μm) or a 200-Hz tactile standard (at a level of 7.6 μm and comparisons in the range of 3.8 to 11.5 μm). The psychometric functions derived from trials with each of the auditory distracter frequencies were non-distinguishable from those of the baseline trials with no auditory distractors.

Substantial differences in approach exist between the detection experiments described in the current paper and the frequency-discrimination experiments of Ro et al.

(2009) and Yau et al. (2009). In the detection experiments (conducted near threshold), both the auditory and tactile stimuli in the A+T condition are relevant to performing the task whereas in the tactile frequency-discrimination experiments (conducted at supra-threshold levels) only the T stimulus is task-relevant during A+T presentations. However, both approaches suggest that the frequency of stimulation within each of the two modalities affects performance on A+T conditions. In the case of the tactile frequency-discrimination experiments conducted by Yau et al. (2009), performance on a 200-Hz tactile target was affected only by the presence of auditory frequencies in the range of 100-300 Hz and on a 400-Hz tactile target by auditory frequencies in the range of 100-400 Hz. Thus, similar to our results in Experiments 1 and 2, perceptual interactions appear to be greater when the frequencies of A and T are more closely spaced and furthermore when both frequencies are within the Pacinian range.

The results of Yau et al. (2009) indicate that subjects were able to effectively ignore interactions of the auditory and tactile tones in performing the intensity-discrimination task but not the frequency-discrimination task. In the case of intensity discrimination, Weber's Law predicts an increase in ΔI with an increase in the level of the standard stimulus that would arise from integration of the auditory and tactile stimuli; thus, subjects may choose to ignore the auditory intensity component in order to maximize their performance. In the case of tactile frequency discrimination, however, performance was strongly affected by the presence of auditory frequencies in the Pacinian range (i.e., below 300 or 400 Hz). In fact, our own analysis of the data of Yau et al. (2009) suggests that performance in the presence of these distracters closely matches what would be predicted from the baseline function for a comparison tone that is the average of the frequency of the tactile comparison tone and the auditory distracter. A similar averaging operation may also be inferred from the results of Ro et al. (2009), described above.

C. Tonotopy, Filtering, and Pathways in the Auditory and Tactile Systems

Tonotopic mapping from the brainstem to the cortex has been demonstrated in neurophysiological studies with animals (for a review see Schreiner et al., 2000) as well as in imaging studies of the human auditory cortex (Romani and Williamson, 1981; Bilecen et al., 1998; Talavage et al., 2000; Talavage et al., 2004). In the perceptual domain, a variety of experiments have shown that the auditory system exhibits critical-band filtering (e.g., Moore et al., 1990; Zwicker 1961; Greenwood, 1961). Interaction of multiple auditory stimuli is greatest when those two stimuli fall within a single critical band, and decreases as the frequency separation between them increases (i.e., as they fall into separate critical bands).

The peripheral tactile receptor system has also been shown to respond to different ranges of frequencies: a "non-Pacinian" channel responding to frequencies ranging from less than 1 to approximately 50 Hz, and a Pacinian channel, responding to frequencies ranging from approximately 50 Hz to 500 Hz (Gescheider et al., 2002; Hamer et al., 1983; Verrillo, 1963; Bolanowski et al., 1988; Verrillo, 1983; Gescheider et al., 2001; Morley and Rowe, 1990; Formby et al., 1992). There is also some evidence for possible frequency selectivity at the level of the somatosensory cortex. The primary somatosensory cortex responds to frequencies in the "flutter" range (i.e., frequencies less than 50 Hz: Harris et al., 2006; Hegner et al., 2007) while the secondary somatosensory cortex responds to frequencies in the "vibration" range (i.e., frequencies between 50 and

500 Hz: Francis et al., 2000; Harrington and Downs, 200; Iguchi et al., 2007). The results of other studies, however, suggest that a frequency organization in S1 may not exist in humans (Hashimoto et al., 1999) or in animal models (Luna et al., 2005; Lafuente and Romo, 2005; Romo et al., 2000; Romo et al., 1998; Hernandez et al., 2000). Psychophysical studies have also shown evidence of "critical-band" filtering in the tactile system although over a frequency range that is greatly compressed compared to that of the auditory system (Markous et al, 1995; Marks, 1979).

Given that recent anatomical studies have shown that the somatosensory system projects to the auditory system (Cappe and Barone, 2005) and that physiological studies have shown that these two sensory systems interact with one another in the auditory cortex (Schroeder et al., 2001; Foxe et al., 2002; Schurmann et al., 2006), our data suggest the possibility of a cross-modal tonotopic mapping. The results from Experiments 1, 2, and 3 indicate that critical-band filtering is exhibited in both the auditory and somatosensory systems and that these filters interact with one another across the different sensory modalities. In comparing the results of Experiments 1 and 2, our data suggest that the auditory and somatosensory filters are of different shapes, with the auditory filters being more sharply defined than those of the tactile system.

Our modeling results are suggestive of different anatomical pathways for cross-modal integration depending on the frequencies of the A and T stimuli. When auditory and tactile stimulus frequencies are similar to each other and within the Pacinian range, cross-modal scores are well-modeled by the ASM. A pathway for within-channel integration may occur through ascending somatosensory inputs to early auditory centers in the brainstem and thalamus. Auditory and tactile sensations may be integrated at these early levels before their combination reaches the auditory cortex. When auditory and tactile frequencies of stimulation are farther apart, cross-modal scores tend to be well-modeled by the PSM, suggesting cross-channel integration. A potential anatomical pathway for this type of integration may be the ascending inputs to the somatosensory cortex, which then project to the auditory cortex. Interactions between auditory and tactile stimuli would take place at the level of the cortex using input derived from independent pathways for each modality.

It has been suggested that the inner ear evolved out of the skin as a highly frequency-specific responder (Fritzsch and Beisel, 2001; Fritzsch et al., 2007). The tactile system may thus serve to extend the range of low-frequency hearing where sensitivity to auditory signals is not as good as at higher frequencies. Recent research suggests that in large mammals such as elephants and lions, vibrational events in the ground may be used for communication (O'Connell-Rodwell et al., 2001). In this light, the tactile and auditory systems could represent a continuum of detectable frequencies, with one sense picking up where the other one leaves off.

V. SUMMARY AND CONCLUSIONS

Our experiments have shown that the detection of combinations of near-threshold auditory and tactile stimuli is dependent on the frequencies of stimulation employed within each modality. When stimulating frequencies in the two modalities are equal or close to one another, detection rates tend to be higher than for combinations employing larger differences in frequency. Observed auditory-tactile performance was compared to the predictions of three different models of integration using single-modality scores as input. Different types of integration were observed with different combinations of auditory and tactile stimuli. In particular, the within-channel integration of the ASM provided a close fit to data for conditions in which the auditory and tactile stimulating frequencies were equal or close to one another and were within the Pacinian frequency range. The cross-channel integration of the PSM tended to provide the best fit to conditions with larger frequency spacings. Little integration of any type was observed for 50-Hz stimulation in both modalities, suggesting that integrative effects may not extend to frequency regions conveyed by non-Pacinian receptors.

Further research is being conducted on auditory-tactile integration with supra-threshold stimuli and concerned in particular with the relation between frequency spacing and loudness. In the auditory domain, it is well established that two-tone stimuli that lie within a critical band are more effectively integrated as far as detection is concerned than two tones that lie in different critical bands. This effect is similar to that observed in our experiments with auditory and tactile stimuli: detection is higher when the frequencies of the auditory and tactile stimuli are equal or closely spaced than when they are farther apart. For loudness, on the other hand, two auditory tonal stimuli are louder when they occupy different critical bands than when they lie within the same critical band. It will be important to determine whether the frequency spacing of auditory and tactile stimuli has a similar effect on perceived strength of combined auditory-tactile stimuli.

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APPENDIX: Auditory Narrowband Noise Combined with Auditory Pure Tones

To test our methods we conducted a purely auditory experiment as a complement to Experiment 1, in which an auditory narrowband noise (NBN) of bandwidth 48 Hz and centered on 250 Hz was substituted for the tactile stimulus. This experiment was conducted on five audiometrically normal subjects (3 females; age ranges 19 to 59). Each subject completed four repetitions of the experimental conditions. One subject (S_{12}) was disqualified after testing because of abnormally high threshold levels for the pure tones. The auditory pure tone (PT) frequencies used were the same as in Experiment 1: 125, 250, 500, 1000, and 2000 Hz. The level of the narrowband noise was determined by the same procedure that was used to determine the levels of the tones (see Sec. II-D).

Figure A1 shows the results of the detection experiment. At threshold, percent-correct values for a single stimulus (PT-alone and NBN-alone) ranged from 69.8%-correct (NBN) to 73%-correct (1000 Hz tone). In the combined PT+NBN presentations, the highest percent-correct score was obtained when the tone was 250 Hz (87.8%-correct), while the response levels were lower for other PT frequencies

Five separate two-way ANOVAs were performed on the arcsine transformed percent-correct scores for the PT-alone, NBN-alone and PT+NBN conditions. All PT frequencies, except 1000 Hz, showed significant effects for Condition (125-Hz: [$F(2,36) = 21.14$, $p < 0.01$]; 250-Hz: [$F(2,36)=42.91$, $p < 0.01$]; 500 Hz: [$F(2,36)= 7$, $p < 0.01$]; 2000 Hz: [$F(2,36)= 20.55$, $p < 0.01$]). For the 1000-Hz condition ([$F(2,36)= 4.42$, $p =0.019$]) the PT+NBN response was significantly higher than the NBN but not the PT response. Only the 1000-Hz and 2000-Hz conditions showed a significant effect of Subject (1000 Hz: [$F(3,26)=10.79$, $p<0.01$]; 2000 Hz: [$F(3,26)=4.39$, $p<0.01$]) and the interaction of Condition and Subject (1000 Hz: [$F(6,36)=7.39$, $p<0.01$]; 2000 Hz: [$F(6,36)=4.26$, $p<0.01$]). For the 1000-Hz condition, a *post hoc* Tukey-Kramer analysis showed that the responses for subject S_{10} were significantly higher than the other 3 subjects, while for the 2000-Hz condition, the *post hoc* analysis showed that responses for S_{10} were significantly higher than for S_6 but not for the other subjects.

A second two-way ANOVA was performed on the arcsine transformed percent-correct scores for the 5 PT+NBN conditions. This analysis showed a significant effect for Condition [$F(4,60)=9.16$, $p<0.01$] and Subject [$F(3,60)=12.44$, $p<0.01$] but not for their interaction [$F(12,60)=1.54$, $p=0.135$]. A *pos hoc* Tukey-Kramer analysis showed that the percent-correct score for the 250-Hz condition was significantly higher than the other conditions, and that scores for S_{10} were significantly higher than those of all other subjects.

The responses were analyzed in terms of the three models (OSCM, PSM and ASM) discussed in Sec. F. The PSM best fit the results of conditions 125 and 500 Hz (both with 94 % passing the chi-squared test). The ASM best fit the results of the 250-Hz condition (with 75% passing), while the OSCM best fit the 1000-Hz and 2000-Hz conditions (with 69% and 81% passing, respectively).

Three previous studies attempted to relate the detection in noise of pairs of auditory stimuli to the detection of the components of the pairs, though all considered the detection of pairs of tones rather than the detection of combinations of tones and narrowband noise. Marill (1956) tested two listeners on the detection of 1-s bursts of 500- and 1100-Hz tones in 57 dB/Hz broadband noise as a function of signal level in a 2I, 2AFC experiment. He then measured the detection of pairs of tones (500, 540), (1060,

1100) and (500, 1100) Hz. He interpreted his results for (1060, 1100) Hz as supporting the ASM and the results for (500, 1100) Hz as supporting the OSCM with the results for (500, 540) Hz lying between the predictions of these two models (he did not consider the PSM). Green (1958) measured the detection of pure tones of frequency 500, 1000, 1823, and 2000 Hz as well as all pairs made up from these tones. Green tested three listeners on the detection of 50, 200, and 1000 ms tone bursts in 60 dB/Hz noise using a 4AFC procedure. He interpreted his results as supporting the PSM for all pairs of tones. Grose and Hall (1997) tested 8 listeners using a 3AFC adaptive procedure with a masker consisting of 20 Hz wide bands of noise presented at 35 dB/Hz. They found that a PSM type model accounted for the detection of pairs consisting of 870- and 1125-Hz tones of duration 400 ms.

The results are fairly consistent with ours if one assumes that the ASM applies to frequency spacings less than 0.3 ERB (Moore et al., 1990), the PSM to spacings between 0.4 and 5 ERB, and the OSCM to spacings greater than roughly 11 ERB. The studies give conflicting results for spacings of 5.5-10.4 ERB, with the findings of Green (1958) supporting the PSM rule, while those of Marill (1956) and us support the OCSM rule.

Figure 1: Single-modality signal levels employed for individual subjects tested in each of the four experiments. Auditory levels are for detection of pure tones in 50–dB SPL broadband noise. Tactile levels are for detection of sinusoidal vibrations presented to the fingertip. Different symbols represent results obtained in different experiments. Some subjects participated in more than one experiment. Solid line indicates the average across subjects and experiments for each frequency. Error bars are 1 SEM.

Figure 2: Summary of results for the Baseline Condition in Experiments 1, 2, and 3. Percent-correct scores for the individual subjects in each experiment are averaged across multiple repetitions per condition; number of repetitions varies by subject, and is equal to or greater than four per subject. AVG is an average across subjects and repetition in each experiment. White bars represent Auditory-alone conditions, grey bars represent Tactile-alone conditions, and black bars represent the A+T Baseline condition with auditory and tactile frequencies = 250 Hz, simultaneous presentation. Error bars are 1 SEM.

Figure 3: Summary of results for Experiment 1 (3a), Experiment 2 (3b), and Experiment 3 (3c). Percent-correct scores are averaged across subjects and sessions. Scores are shown for A-alone (white bars), T-alone (light grey bars), and for combined A+T conditions (dark grey bars). In Experiment 1, scores are shown as a function of auditory frequency with tactile frequency = 250 Hz. In Experiment 2, scores are shown as a function of tactile frequency with auditory frequency = 250 Hz. In Experiment 3, scores are shown as a function of frequency where auditory = tactile. Error bars are 1 SEM.

Figure 4: Predicted vs. Observed values for the two models of integration, showing data for Conditions 1-2, 2-3, 3-1, 3-2, 3-3, and 3-4. The top two rows (4a and 4b) represent the Baseline condition from all three experiments (Auditory = Tactile Frequency = 250 Hz). Left column is data from Experiment 1, middle column is data from Experiment 2 and right column is data from Experiment 3. Bottom two rows (4c and 4d) represent remaining data from Experiment 3 in which the auditory and tactile frequencies are equal (50, 125 and 400 Hz). Panel (a) Pythagorean Sum (Experiments 1, 2, and 3); Panel (b) Algebraic Sum (Experiments 1, 2, and 3); Panel (c) Pythagorean Sum (Experiment 3); Panel (d) Algebraic Sum (Experiment 3). Each sub-experiment is delineated by shape (see legend). Open symbols indicate that the observed value failed the Chi-Squared test and filled symbols indicate the observed value passed the Chi-Squared test.

Figure 5: Ratio of the Observed d-Prime values to the Predicted D-Prime values for each of the three models averaged across subjects and repetitions of each experimental condition. Panel (a) Ratios for Experiment 1, in which the tactile frequency = 250 Hz and the auditory frequency was varied between 125 and 2000 Hz. Panel (b) Ratios for Experiment 2, in which the auditory frequency = 250 Hz and the tactile frequency was varied between 50 and 400 Hz. Panel (c) Ratios for Experiment 3, in which the auditory and tactile frequencies were equal and co-varied between 50 and 400 Hz. The horizontal bar on each graph indicates a ratio of 1.0 (i.e., Observed = Predicted values). The dark grey bars represent the Optimal Single Channel Model, the grey bars represent the Pythagorean Sum Model, and the light grey bars represent the Algebraic Sum Model. Error bars are 1 SEM.

Figure A1: %-correct scores averaged across 4 subjects and 4 repetitions per condition. Scores are shown for auditory PTs alone (white bars), auditory NBN alone (light grey bars) and for combined PT+NBN (dark grey bars). Scores are shown as a function of auditory PT frequency with NBN centered at 250 Hz and bandwidth of 48 Hz. Error bars are 1 SEM.

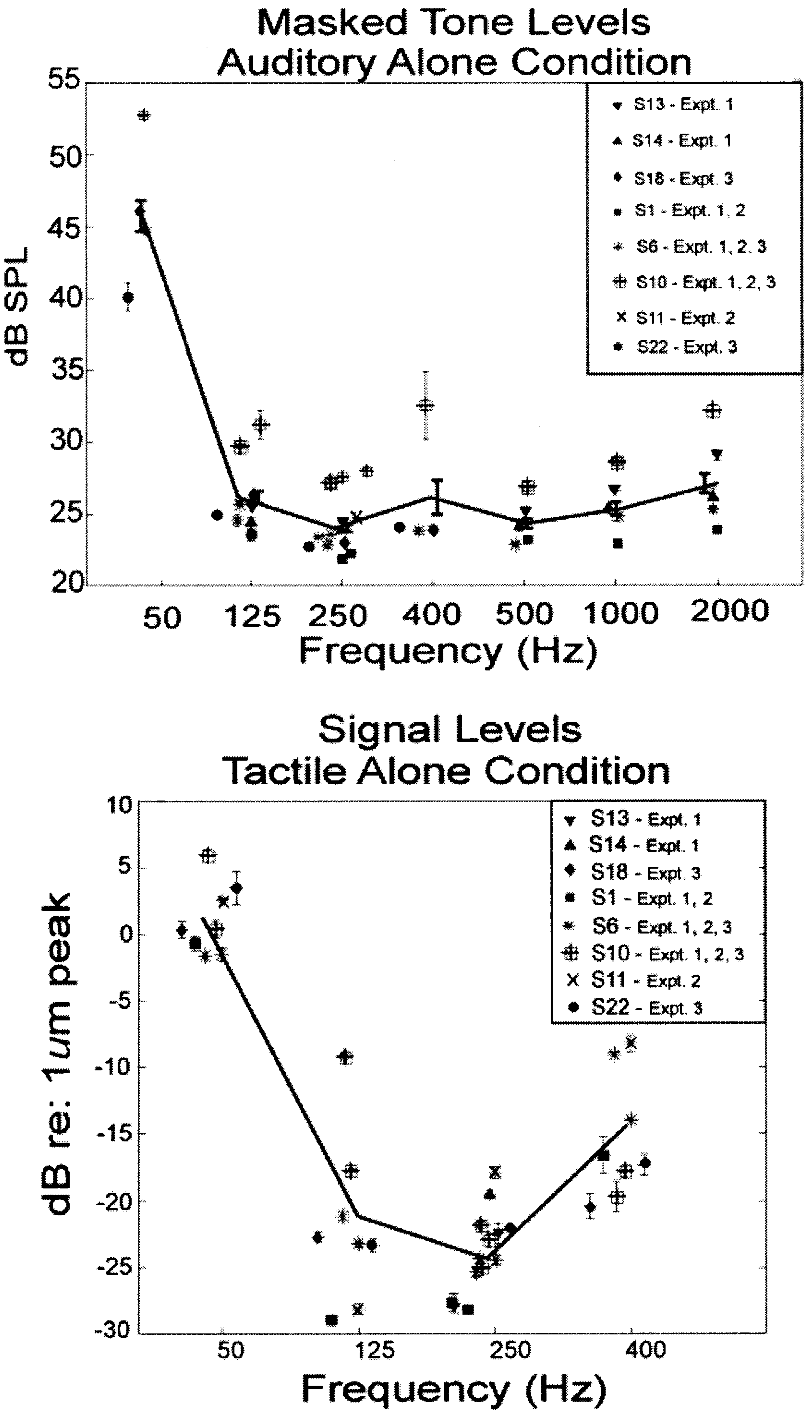
Masked Tone Levels
Auditory Alone Condition
dB SPL
55
50
45
40
35
30
25
20
50
125
250
400
500
1000
2000
Frequency (Hz)
▼ S13 - Expt. 1
▲ S14 - Expt. 1
♦ S18 - Expt. 3
■ S1 - Expt. 1, 2
* S6 - Expt. 1, 2, 3
⊕ S10 - Expt. 1, 2, 3
× S11 - Expt. 2
● S22 - Expt. 3
Signal Levels
Tactile Alone Condition
dB re: 1um peak
10
5
0
-5
-10
-15
-20
-25
-30
50
125
250
400
Frequency (Hz)
▼ S13 - Expt. 1
▲ S14 - Expt. 1
♦ S18 - Expt. 3
■ S1 - Expt. 1, 2
* S6 - Expt. 1, 2, 3
⊕ S10 - Expt. 1, 2, 3
× S11 - Expt. 2
● S22 - Expt. 3

Figure 1

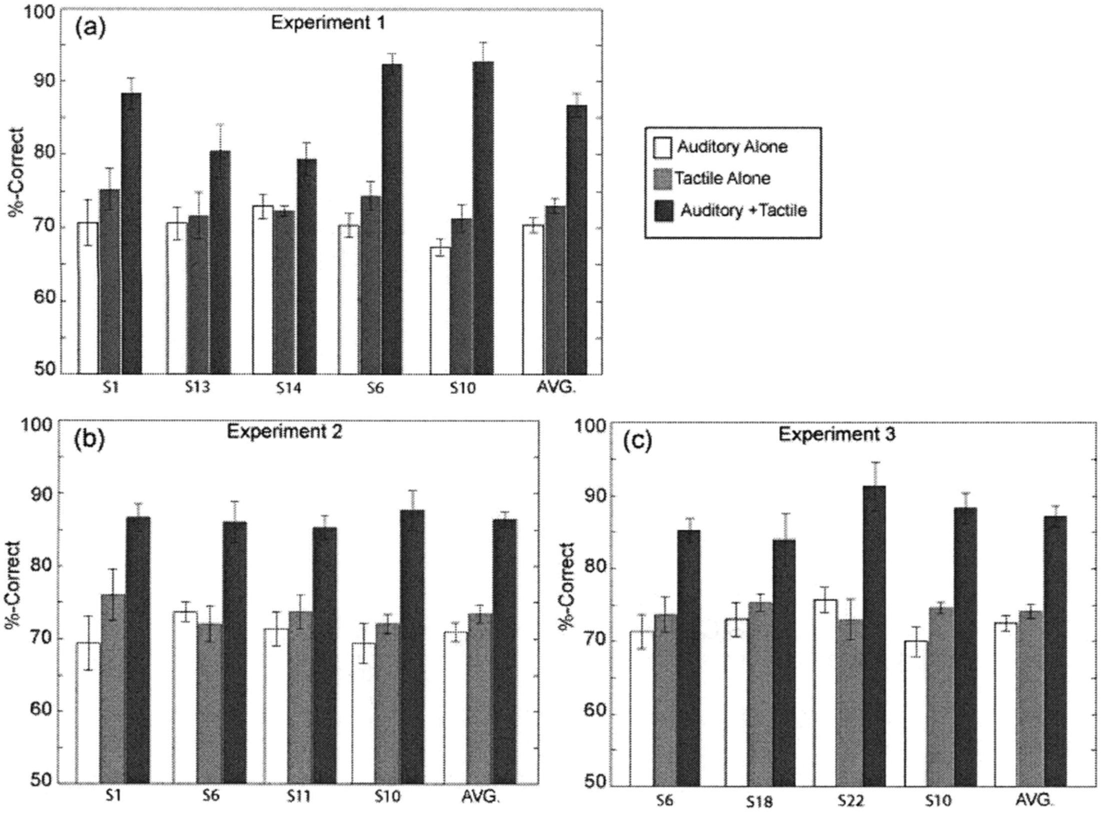
(a)
Experiment 1
%-Correct
100
90
80
70
60
50
S1
S13
S14
S6
S10
AVG.
□ Auditory Alone
▨ Tactile Alone
■ Auditory +Tactile
(b)
Experiment 2
%-Correct
100
90
80
70
60
50
S1
S6
S11
S10
AVG.
(c)
Experiment 3
%-Correct
100
90
80
70
60
50
S6
S18
S22
S10
AVG.

Figure 2

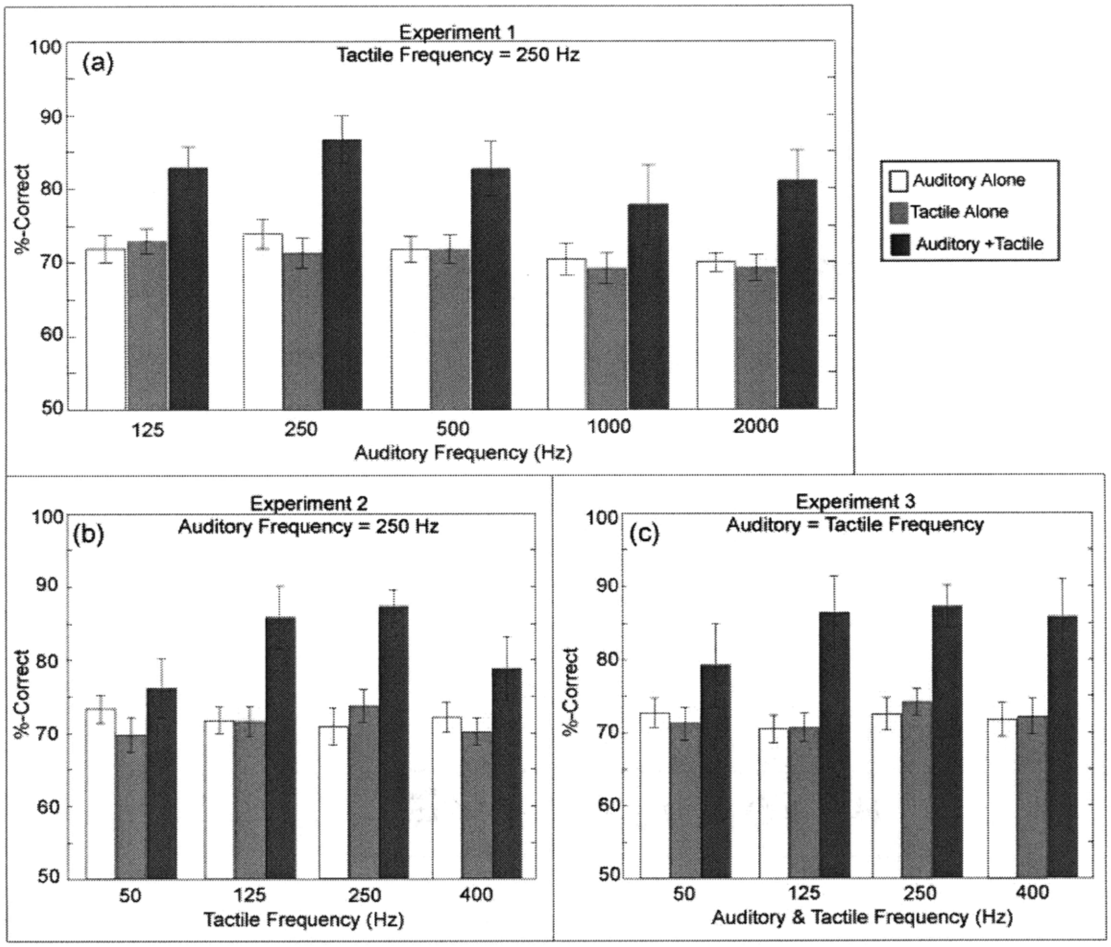
Experiment 1
Tactile Frequency = 250 Hz
(a)
%-Correct
100
90
80
70
60
50
125
250
500
1000
2000
Auditory Frequency (Hz)
Auditory Alone
Tactile Alone
Auditory +Tactile
Experiment 2
Auditory Frequency = 250 Hz
(b)
%-Correct
50
125
250
400
Tactile Frequency (Hz)
Experiment 3
Auditory = Tactile Frequency
(c)
%-Correct
50
125
250
400
Auditory & Tactile Frequency (Hz)

Figure 3

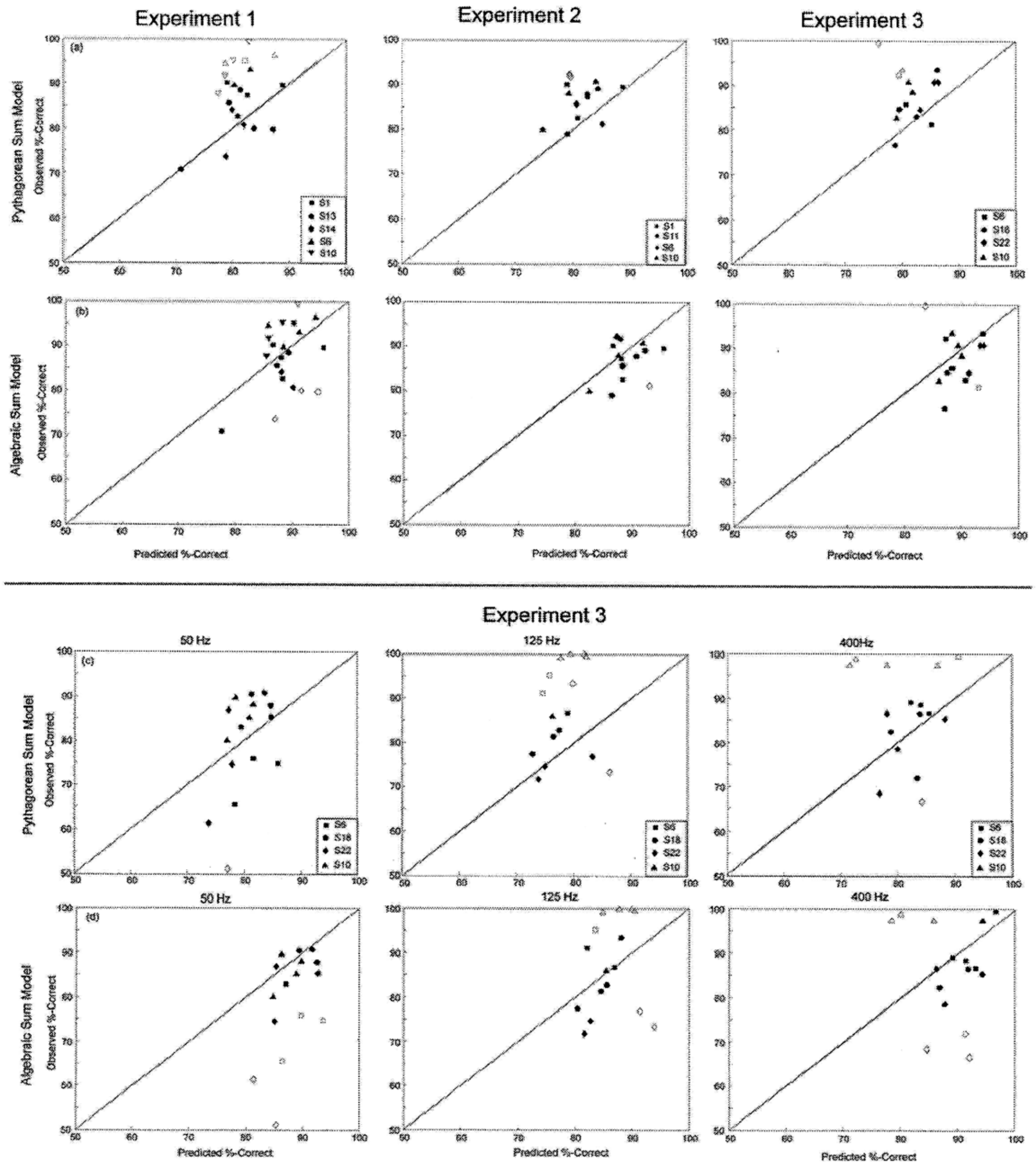
Experiment 1
Experiment 2
Experiment 3
Pythagorean Sum Model
Observed %-Correct
Algebraic Sum Model
(a)
(b)
S1
S13
S14
S6
S10
S1
S11
S6
S10
S6
S18
S22
S10
Predicted %-Correct
Experiment 3
50 Hz
125 Hz
400Hz
(c)
(d)
400 Hz
50
60
70
80
90
100

Figure 4

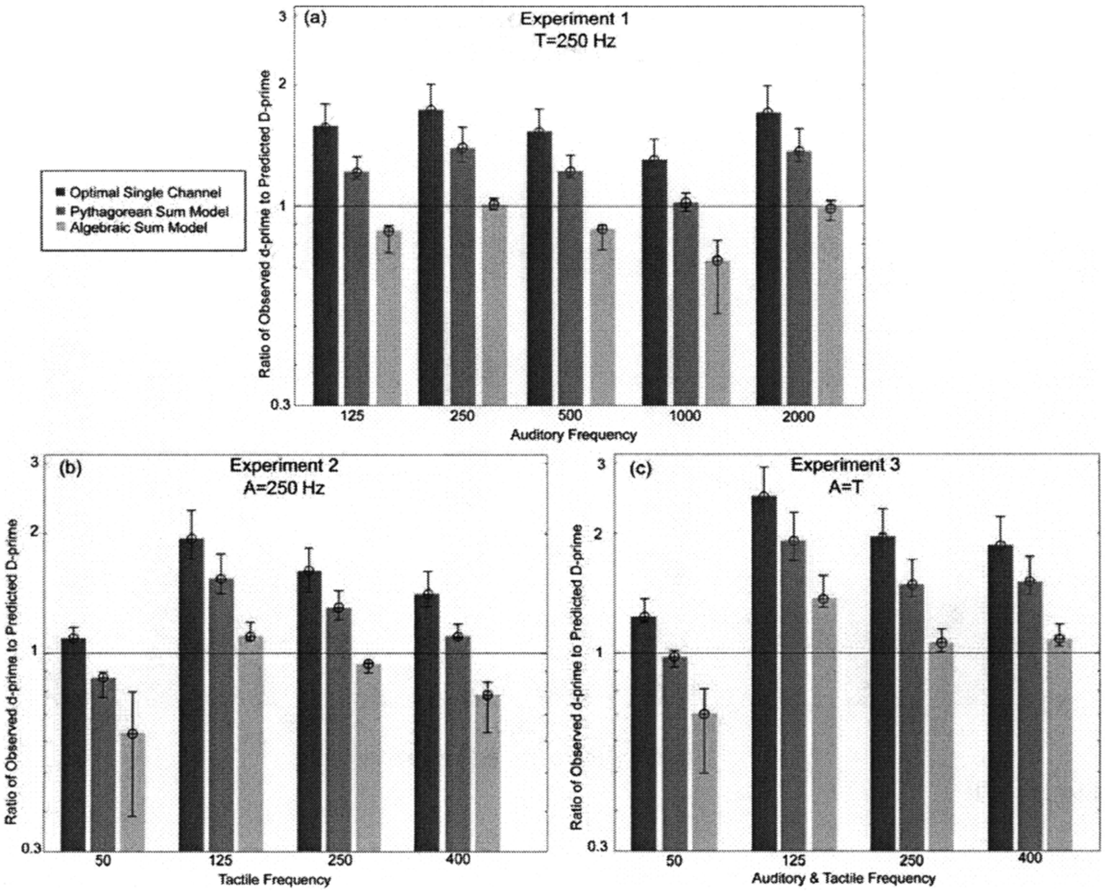
(a)
Experiment 1
T=250 Hz
Optimal Single Channel
Pythagorean Sum Model
Algebraic Sum Model
Ratio of Observed d-prime to Predicted D-prime
3
2
1
0.3
125
250
500
1000
2000
Auditory Frequency
(b)
Experiment 2
A=250 Hz
Ratio of Observed d-prime to Predicted D-prime
3
2
1
0.3
50
125
250
400
Tactile Frequency
(c)
Experiment 3
A=T
Ratio of Observed d-prime to Predicted D-prime
3
2
1
0.3
50
125
250
400
Auditory & Tactile Frequency

Figure 5

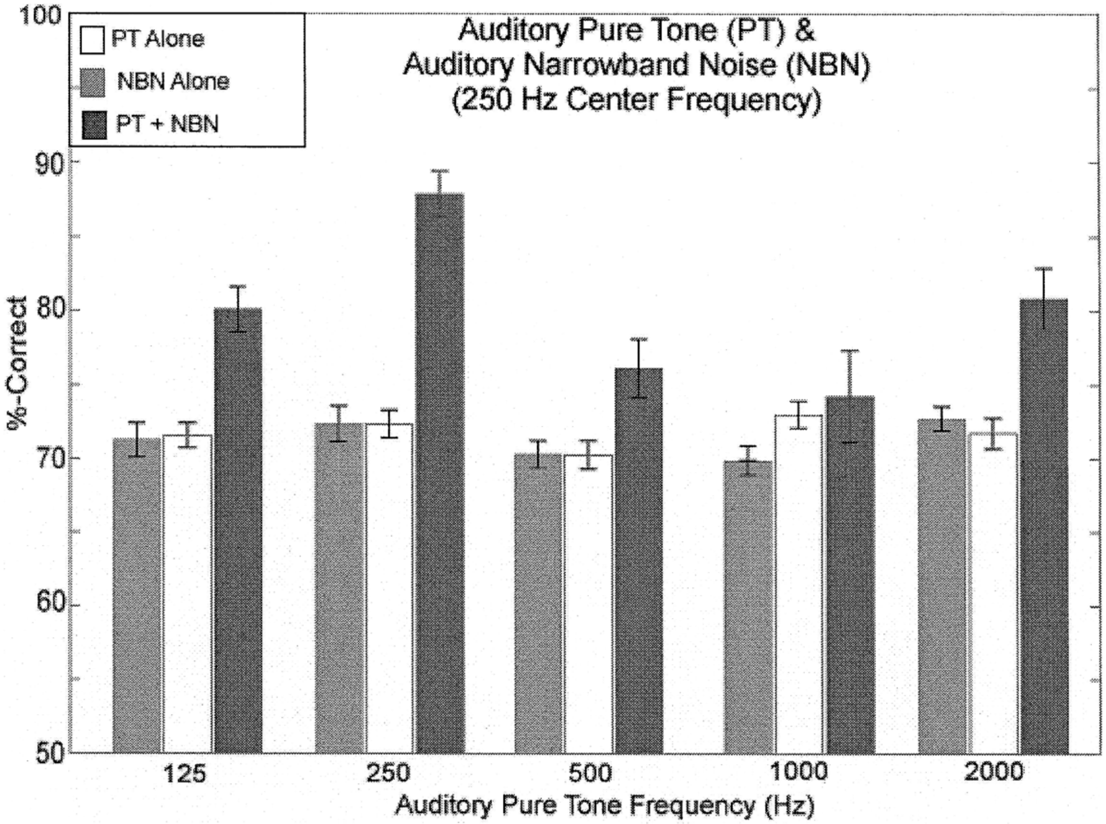
Auditory Pure Tone (PT) &
Auditory Narrowband Noise (NBN)
(250 Hz Center Frequency)
PT Alone
NBN Alone
PT + NBN
%-Correct
100
90
80
70
60
50
125
250
500
1000
2000
Auditory Pure Tone Frequency (Hz)

Figure A1

Table I: Description of experimental conditions studied in Experiments 1, 2 and 3. In all experiments, the duration of the auditory and tactile stimulus was always 500 ms and the stimuli were presented simultaneously.

Experiment 1: Variable Studied: ***Auditory Frequency***				
Condition	**Frequency (Hz)**		**Subjects**	**# Repetitions**
	Auditory Stimulus	**Tactile Stimulus**		
1-1	125	250	$S_1,S_6,S_{10},S_{13},S_{14}$	6
1-2	250	250	$S_1,S_6,S_{10},S_{13},S_{14}$	6
1-3	500	250	$S_1,S_6,S_{10},S_{13},S_{14}$	6
1-4	1000	250	$S_1,S_6,S_{10},S_{13},S_{14}$	6
1-5	2000	250	$S_1,S_6,S_{10},S_{13},S_{14}$	6
Experiment 2: Variable Studied: ***Tactile Frequency***				
2-1	250	50	S_1,S_6,S_{10},S_{11}	4
2-2	250	125	S_1,S_6,S_{10},S_{11}	4
2-3	250	250	$S_1^1,S_6^2,S_{10}^2,S_{11}$	4

2-4	250	400	S_1,S_6,S_{10},S_{11}	4
Experiment 3: Variable Studied: ***Auditory Frequency, Tactile Frequency***				
3-1	50	50	S_6,S_{10},S_{18},S_{22}	4
3-2	125	125	S_6,S_{10},S_{18},S_{22}	4
3-3	250	250	S_6[3],S_{10},S_{18},S_{22}	4
3-4	400	400	S_6,S_{10},S_{18},S_{22}	4

[1] S_1 data for Condition 2-3 were the measurements made in Condition 1-2.

[2] S_6 and S_{10} data for Condition 2-3 used Baseline data from Wilson et al. (2009)

[3] S_6 data for condition 3-3 used Baseline measurements from Wilson et al.(2009)

Table II: Chi-Squared Tests: Predicted vs. Observed. This table enumerates the number of observations that have passed/failed the Chi-Squared goodness of fit test for each of the three models (i.e., Optimal Single Channel, Pythagorean Sum and Algebraic Sum).

Experimental Condition	***Auditory Freq.***	***Tactile Freq.***	***Total***	***Optimal Single Channel***			***Pythagorean Sum***			***Algebraic Sum***		
				Pass	***Fail***	***Under predict Fail***	***Pass***	***Fail***	***Under predict Fail***	***Pass***	***Fail***	***Under predict Fail***
1-2	250	250	21	11 (52%)	10	10	14 (67%)	7	7	17 (81%)	4	1
2-3	250	250	16	10 (63%)	6	6	13 (81%)	3	3	15 (94%)	1	0
3-3	250	250	16	9 (57%)	7	7	13 (81%)	3	3	14 (88%)	2	1
Totals			*53*	*30* *(57%)*	*23*	*23*	*40* *(76%)*	*13*	*13*	*46* *(87%)*	*7*	*2*
1-2	125	250	22	15 (68%)	7	7	19 (86%)	3	3	15 (68%)	7	1
1-2	250	250	21	11 (52%)	10	10	14 (67%)	7	7	17 (81%)	4	1
1-3	500	250	22	15 (68%)	7	7	17 (77%)	5	4	13 (59%)	9	1
1-4	1000	250	22	11 (50%)	11	8	16 (73%)	6	2	14 (64%)	8	0
1-5	2000	250	22	12 (55%)	10	10	13 (59%)	9	6	12 (55%)	10	3
Totals			*109*	*64* *(59%)*	*45*	*42*	*79* *(73%)*	*30*	*22*	*71* *(65%)*	*38*	*6*

2-1	250	50	16	15 (94%)	1	1	15 (94%)	1	0	9 (56%)	7	0
2-2	250	125	16	10 (63%)	6	6	11 (69%)	5	5	14 (88%)	2	2
2-3	250	250	16	10 (63%)	6	6	13 (81%)	3	3	15 (94%)	1	0
2-4	250	400	16	12 (75%)	4	4	12 (75%)	4	2	11 (69%)	5	0
Totals			*64*	*47 (73%)*	*17*	*17*	*51 (80%)*	*13*	*10*	*49 (77%)*	*15*	*2*
3-1	50	50	16	10 (63%)	6	5	15 (94%)	1	0	11 (69%)	5	0
3-2	125	125	16	8 (50%)	8	8	8 (50%)	8	7	9 (57%)	7	5
3-3	250	250	16	9 (57%)	7	7	13 (81%)	3	3	14 (88%)	2	1
3-4	400	400	16	10 (63%)	6	6	10 (63%)	6	5	10 (63%)	6	3
Totals			*64*	*37 (58%)*	*27*	*26*	*46 (72%)*	*18*	*15*	*44 (69%)*	*20*	*9*

Chapter 4. Effects of Frequency at Supra-Threshold Levels

The work described in this chapter is being submitted to the *Journal of the Acoustical Society of America* under the title "Perceptual interactions in the loudness of combined auditory and vibrotactile stimuli"

INTRODUCTION

Our previous research on auditory-tactile perceptual interactions (Wilson et al., 2009, Wilson et al., under review) provides evidence for the integration of near threshold level auditory (A) and tactile (T) tonal stimuli when presented simultaneously in an objective detection context. Specifically, we found that for 250-Hz auditory and tactile stimuli, performance was highest when the two stimuli were presented synchronously, that the increase in performance was not affected by the relative phase of the auditory and tactile sinusoidal stimuli and that performance for non-overlapping stimuli improved only if the tactile stimulus preceded the auditory stimulus. Additionally, we found the highest rates of detection for the combined-modality stimulus when frequencies in the two modalities were equal or closely spaced (and were within the Pacinian range, i.e., 50 Hz and higher). These results suggested that perceptual integration of auditory and tactile stimuli at near-threshold levels depends both on absolute frequency and relative frequency of stimulation within each modality. To extend this research to supra-threshold stimuli is nearly impossible because of the difficulty of measuring detection for stimuli well above threshold. Instead we examined auditory-tactile integration as a function of how the loudness of auditory and tactile stimuli would combine using the frequency relationship determined previously as a basis for this study.

In the auditory domain, it is well established (e.g., Marill, 1956) that two-tone stimuli that lie within a critical band are more effectively integrated, as far as detection is concerned, than two tones that lie in different critical bands. This effect is similar to that observed in our experiments with auditory and tactile stimuli: detection is higher when the frequencies of the auditory and tactile stimuli are equal or closely spaced than when they are farther apart. For loudness, on the other hand, two auditory tonal stimuli are louder when they occupy different critical bands than when they lie within the same critical band. It is important to determine whether the frequency spacing of auditory and tactile stimuli has a similar effect on perceived strength of combined auditory-tactile stimuli at supra-threshold levels.

There have been several studies investigating auditory-tactile interaction using loudness as a metric. These studies have demonstrated that the combined loudness of an auditory-tactile stimulus can exceed that of the auditory component alone (Schurmann et al., 2004; Gillmeister and Eimer, 2007; Yarrow et al., 2008) or of the tactile component alone (Gescheider et al., 1974). For example, Schurmann et al. (2004) found that the average intensity required to produce equal loudness of an auditory-only reference tone was 12-13% (roughly 0.5 dB) lower under the combined auditory-tactile condition compared with the auditory-alone condition, thus suggesting a facilitative interaction between the auditory and tactile stimuli. Gillmeister and Eimer (2007) found that presentation of a tactile square-wave stimulus increased magnitude estimates of a white noise auditory stimulus by roughly 0.5 dB when the stimuli were presented synchronously and in spatial coincidence. Yarrow et al. (2008) measured the effect of a 120-Hz 34-dB SL tone on the loudness of a partially masked (71 dBA white noise) 120

Hz auditory tone using the method of constant stimuli to estimate points of subjective equality. On average, the loudness of the auditory tone increased by 12-13% when the tactile stimulus was presented. They found that the vibration alone produced a loudness equivalent to a 0 dB SL masked tone, and that the vibration plus a 0 dB SL tone was equivalent to 2.5 dB SL masked tone, with smaller increases in matched level for more intense tones. It should be noted, however, that based on the results of other experiments, Yarrow et al. (2008), however, attribute the increase in loudness to a bias effect, concluding that the tactile stimulus "does not affect auditory judgments in the same manner as a real tone." Finally, Gescheider et al. (1974) observed that magnitude estimates of a tactile vibratory signal were increased in the presence of a simultaneous auditory tone.

We used a matching paradigm to measure the level of an auditory probe tone as its loudness was compared with either a two-tone auditory complex or a two-tone auditory-tactile complex (i.e., one pure tone presented through each of the two sensory modalities). We modeled our experiment on the classical study of auditory critical bands by Zwicker et al. (1957) who found that the matching level of an auditory probe tone remained constant when the frequencies were within one critical band, but increased when the frequencies of the tone complex fell outside of one critical band. Since the loudness of pure tones increases with level, this implies that the loudness of a tone complex of constant power is constant if the tone components fall within one critical band, but increases as they fall in adjacent critical bands.

In our study, a number of auditory and tactile tonal stimuli were equated in loudness to a fixed-level auditory probe tone. We then determined the level of the probe tone that matched the loudness of pairs of auditory tones or a combination of auditory-tactile tones. The frequencies chosen for the A+A tones represented within or outside critical band separations as specified for auditory-alone conditions (Zwicker, 1961; Swets et al., 1962). For the A+T signals, the tactile tones were either the same frequency as the auditory tone or different by substantial amounts.

EXPERIMENTS

We tested five subjects (1 female; 18-39 years; median age 22 years; all audiometrically normal) after obtaining informed consent. Our experimental setup was similar to previous experiments described in detail in Wilson et al. (2009). In all presentations, the auditory and tactile stimuli were accompanied by 55 dB SPL broadband auditory noise to eliminate possible auditory artifacts from the tactile device. Stimuli were pulsed on with a 500-ms duration including 20 ms on/off ramps. The tactile stimulus was presented to the tip of the left middle finger through an Alpha-m Corporation vibrator. The auditory stimuli were presented diotically via Sennehiser HD580 headphones.

The two stimuli in each combined condition were simultaneous. All sinusoidal stimuli had a starting phase of 0°. We measured auditory masked thresholds and tactile absolute thresholds by an adaptive three-interval, two-alternative forced-choice procedure converging at the 70%-correct mark (Levitt, 1971). Auditory thresholds were measured for frequencies of 200, 250, 300, and 547 Hz. Tactile thresholds were measured for frequencies of 20, 250, and 400 Hz. All stimuli were then equated in loudness to a 200-Hz auditory tone at a level of 25 dB above threshold (SL). The loudness matching paradigm, which was similar to that of Silva and Florentine (2006) and Jesteadt (1980), employed a two-interval adaptive comparison in which the probe was presented randomly in one interval and the reference was presented in the other interval. Two interleaved tracks were presented randomly in a given run. One track contained an initial probe level set much higher than the reference level and a second track contained an initial probe level set much lower than the reference level. The subject was instructed to select which interval was "stronger" and the probe level was adjusted adaptively to the 50%-correct convergence mark. Each run yielded two loudness matches, based on the final probe levels from each of the two tracks.

Tones with levels equated in loudness to the 25-dB SL 200-Hz auditory tone, i.e. auditory tones 250, 300, and 547 Hz and tactile tones of 20, 250, and 400 Hz were then combined into auditory-auditory (A+A) or auditory-tactile (A+T) reference stimulus pairs. The 200-Hz tonal auditory probe stimulus was then matched in loudness (same paradigm as before) to 6 different pairs of stimuli: (1) A (250 Hz) + A (300 Hz), same critical band, (CB); (2) A (250 Hz) + A (547 Hz), different CBs; (3) A (250 Hz) + T (250 Hz); (4) A (547 Hz) + T (250 Hz); (5) A (250 Hz) + T (400 Hz); and (6) A (250 Hz) + T (20 Hz). The adaptive loudness-matching process was repeated four times per condition per subject resulting in eight values per condition.

RESULTS

Figure 1 shows the results of the loudness matching experiment averaged across five subjects and four repetitions of each condition (resulting in eight measurements which were averaged together for each subject). The average level of the 200-Hz auditory probe when set to 25 dB SL was 51.6 dB SPL. The average levels of the auditory pure tones when matched to the 25-dB SL 200-Hz tone were 49.8 dB SPL (250 Hz), 49.2 dB

(300 Hz), and 47.7 dB (547 Hz). The average levels of the tactile tones when matched to the 25-dB SL 200-Hz auditory tone were -12.3 dB *re* 1 μm peak (250 Hz), -6.9 dB (400 Hz), and 5.1 dB (20 Hz).

We found that presenting two equal-loudness auditory stimuli required a 3.0-dB increase in the probe level to match the loudness when the two frequencies were within one critical band [A (250 Hz) + A (300 Hz)] and a 4.5-dB increase when the two stimuli were in different critical bands [A (250 Hz) + A (547 Hz)]. Presenting an auditory and a tactile tone led to a 5.2-dB increase when the two frequencies were the same (250 Hz) but a 7.0-dB increase when the auditory frequency was greater [A (547 Hz) + T (250 Hz)], a 7.3-dB increase when the tactile frequency was greater [A (250 Hz) + T (400 Hz)], and an 8-dB increase when the tactile frequency was lower [A (250 Hz) + T (20 Hz)].

Paired t-tests between the two A+A conditions showed, as expected, a significant difference between the matching probe levels (p = 0.00013). Paired t-tests between the A+T conditions showed that the probe level in the equal-frequency condition [A (250 Hz) + T (250 Hz)] was significantly lower than all other A+T conditions (all p-values < 0.001). Additional paired t-tests showed that matching probe levels in the [A (547Hz) + T (250 Hz)] and the [A (250 Hz) + T (400 Hz)] conditions were not significantly different from one another (p = 0.53), and neither were the probe levels in the [A (250 Hz) + T (400 Hz)] and [A (250 Hz) + T (20 Hz)] conditions (p=0.14), while the probe levels in the [A (547 Hz) + T (250 Hz)] and the [A (250 Hz) + T (20 Hz)] conditions were significantly different from one another (p = 0.02). We obtained a similar pattern of results when we conducted loudness-matching experiments with 250 Hz tactile tones and 250 and 547 Hz auditory tones that were individually equated in SL rather than loudness.

DISCUSSION

Recent neurophysiological studies have shown that the auditory and tactile systems interact in the central nervous system (Schroeder et al., 2001; Foxe et al., 2002; Schurmann et al., 2006) and several psychophysical studies have shown a strong facilitative relationship between the two systems that is dependent on temporal and frequency similarity (Schurmann et al., 2004; Yarrow et al., 2008; Gillmeister and Eimer, 2007; Jousmaki & Hari, 1998; Guest et al., 2002; Schnupp et al., 2005; Wilson et al, 2009; Wilson et al., under review; Yau et al., 2009; Ro et al., 2009). Our results confirm those of Gillmeister and Eimer (2007), Yarrow et al. (2008), and Schurmann et al. (2004), who demonstrated that the combined loudness of an auditory-tactile stimulus exceeds that of the auditory component alone. Further our results indicate that the summation of loudness between auditory and tactile stimuli is frequency dependent, with greater loudness increases in the case of greater frequency separation between the auditory and tactile tones, as is found in the purely auditory studies of loudness matching (Zwicker et al., 1957).

Our auditory-only (A+A) results are consistent with those reported by Zwicker et al. (1957), who showed that as the frequency separation between components in an auditory tone complex increases beyond a critical band, the level of a loudness-matched auditory probe tone increases as well. Our results further suggest that a similar frequency relationship exits between the auditory and tactile senses, the level of the matched probe tone being larger when the auditory and tactile tones are different compared with when they are equal. The greatest increase in probe level was found when the tactile stimulus was 20 Hz, a frequency outside the range of the Pacinian channel (which is most sensitive to 250-Hz sinusoids), and which could be considered a different physiological channel from the Pacinian channel (Marks, 1979; Markous et al., 1995). Nearly the same increase in matching level is found for 400-Hz tactile sinusoids, suggesting that there may be a critical band organization in the tactile channel associated with the Pacinian system (e.g., Bensmaia et al., 2005) or that some form of cross-modal critical band relation may exist between auditory and tactile stimuli.

Recently Leibold et al. (2007) and Leibold and Jesteadt (2007) have investigated the relationship between the loudness of 5-tone complexes and the masked threshold of individual components in the presence of the other four components. They found that when the overall spacing of the complex increased from 0.7 to 3.5 ERB, the masked threshold of the outer two tones decreased by roughly 6 dB while the level of a tone at the center of the complex that was matched in loudness increased by 5 dB. We found that when the spacing of an auditory two-tone complex increased from 0.9 to 4.5 ERB the matched tone level increased by 1.5 dB. Our findings for auditory-tactile interactions are similar to this. Consider a 250 Hz auditory tone: the greatest detectability occurs when it is paired with a 250-Hz tactile tone; when it is paired with a 500 Hz tactile tone detectability is reduced from 86.6% to 82.0% (Wilson et al., under review). On the other hand, when a tactile 250-Hz tone is paired with an auditory 547-Hz tone instead of an auditory 250-Hz tone, the level of a tone that is matched in loudness must be increased by 1.8 dB. These results imply that as the interaction (as measured by mutual masking or detectability) between the tones that comprise a multi-tone complex decreases the loudness of the complex increases both for auditory-auditory and auditory-tactile stimuli.

While our previous study examined the relationship between auditory and tactile frequency at near-threshold levels of detection (Wilson et al., under review), our current study extends this work by showing that the frequency relationship found at near-threshold levels is preserved at supra-threshold stimulus levels. This finding has important implications for stimuli in the real-world, as most of our day-to-day environmental interactions occur at supra-threshold levels. For example, our perception of texture is highly influenced by the interaction of auditory and tactile inputs to our sensory systems (Jousmaki and Hari, 1998). Language production may also be influenced by the perception of self-produced speech sounds and by the vibrations caused by these productions in the speaker's own vocal tract and lips. While the sense of hearing extends in the lower range to roughly 20 Hz, the sense of touch extends to frequencies below 1 Hz. With significant interactions between auditory and tactile stimuli at supra-threshold levels, it is possible that the sense of touch extends the sense of hearing to frequencies below the audible range.

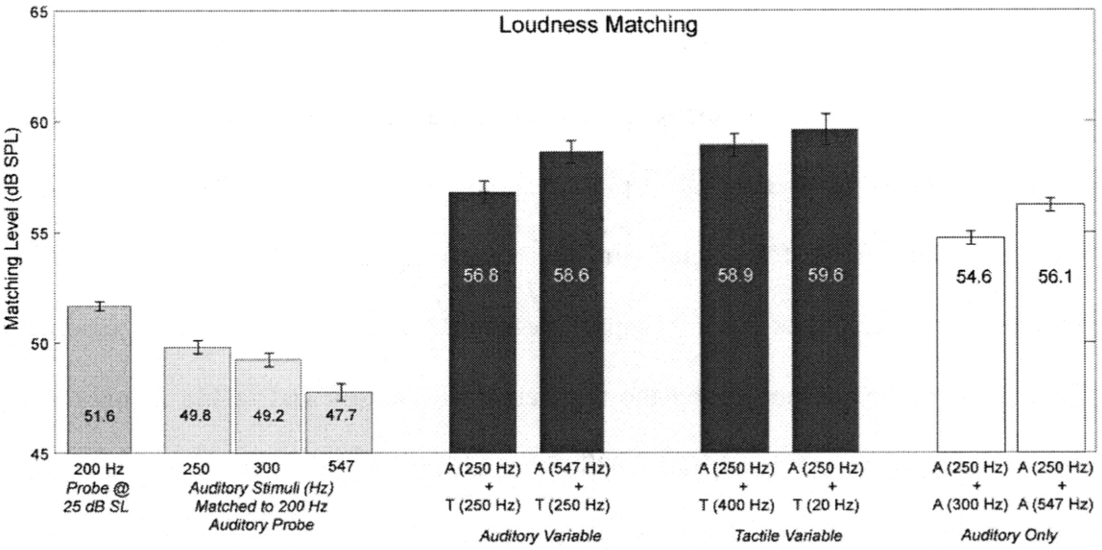

Figure 1 SPL of auditory probe averaged across 5 subjects with 8 repetitions per condition. The dark grey bar represents the average sound pressure level of the 200-Hz auditory probe at 25 dB SL; the light grey bars represent the average levels of the auditory pure tones when matched to the 25-dB SL 200-Hz tone. The black bars represent the level of the probe when matched to a combined auditory-tactile reference stimulus and the white bars represent the level of the probe when matched to a two-component auditory reference stimulus. Error bars are one SEM.

Chapter 5. Effects of Relative Intensity

I. INTRODUCTION

This experiment examined the effects of varying the intensity of a 250-Hz auditory or vibrotactile stimulus on detection. We explored the effect on A+T interaction when signal levels were increased along the psychometric function, rather than at the detection threshold. We used as our measure of performance the percentage-correct score (or sensitivity index d') and varied the sensation level of the auditory and tactile tones relative to one another.

II. METHODS

The experimental procedure used is similar to that employed in the Baseline Experiment explained in detail in Chapter 2 of this document. In all presentations, the auditory and tactile stimuli were accompanied by a 50-dB SPL broadband auditory noise to eliminate possible auditory artifacts from the tactile device. Each stimulus was 500 ms long with 20 ms on/off ramps. The tactile stimulus consisted of a 250-Hz sinusoid and was presented to the tip of the left middle finger through an Alpha-m Corporation vibrator. The auditory stimuli were 250-Hz sinusoids and were presented diotically via Sennehiser HD580 headphones. Data were obtained from 5 audiometrically normal subjects (two female) and ranged in age from 21 to 39 years (median age of 22 years). The two stimuli in each of the combined conditions were simultaneous. All sinusoidal stimuli had a relative starting phase of 0 degrees.

Threshold measurements of the single modalities were made prior to combined testing. Auditory measurements were masked thresholds and tactile measurements were absolute thresholds. A 3-Interval, 2-Alternative forced choice (3-I, 2-AFC) adaptive procedure was performed for both the auditory-alone and the tactile-alone stimuli in order to estimate the subjects' thresholds at the 70%-correct level of detection (Levitt, 1971). Stimuli were then presented for 75 trials in a 2-interval, 2-alternative forced-choice (2-I, 2-AFC) experiment using the method of constant stimuli. The subject's task was to determine which of the two intervals contained the signal. The level of each signal was adjusted separately until between 49-57 correct responses (in a 75-trial run) were obtained, i.e., within one standard deviation of 70.7% correct. The resulting levels of the A-alone and T-alone stimuli were defined as 0 dB SL. A combined-stimulus run was then performed using the signal levels determined for each of the two stimuli in a given pair. Four intensity combinations were tested in the A+T conditions: 1) Auditory at 0 dB SL + Tactile at 0 dB SL, the Baseline Condition; 2) A at 2 dB SL + T at 0 dB SL; 3) A at 0 dB SL + T at 2 dB SL; and 4) A at 2 dB SL + T at 2 dB SL.

Results were compared with predictions of three models: Optimal Single Channel Model (OSCM) which predicts that the d-prime of the combined condition is the greater of the individual sense conditions (i.e., the maximum of either auditory or tactile); the Pythagorean Sum Model (PSM) which predicts that the d-prime in the combined condition is the square root of the sum of the squares of the A-alone and T-alone d-primes; and the Algebraic Sum model (ASM), which predicts that the d-prime is the simple sum of the A-alone and T-alone d-primes. The resulting %-correct is back-calculated from the combined d-prime value using the cumulative of the Gaussian distribution function, ϕ.

III. RESULTS

Figure 1 shows the effect of selectively increasing the intensity of the auditory or tactile component by 2 dB. On average, scores for the A-alone (0 dB SL) and T-alone (0 dB SL) were 70.9 ± 0.8 %-Correct and 71.02 ± 0.9 %-Correct, respectively, while the scores for the A-alone (2 dB SL) and T-alone (2 dB SL) were 79.9 ± 1.5 %-correct and 77.9 ± 2.5 %-Correct, respectively. Scores for the single-modality, 0 dB SL levels are consistent with previous results (Wilson et al., 2009).

In the Baseline condition (A, T, A+T all at 0 dB SL), combined A+T scores increased by 15 percentage points over the A-alone and T-alone scores, resulting in an average response of 86.1 ± 1.5 %-correct, consistent with results previously reported in Wilson et al. (2009). Responses to the three other combined A+T conditions showed minimal increase over the Baseline response. Increasing A by 2 dB resulted in a combined A+T score increase of 8 percentage points over the (A+2)-alone score (87.8 ± 1.8 %-correct) while increasing T by 2 dB resulted in a combined A+T score increase of 9 percentage points over (T+2)-alone score (87.4 ± 1.6 %-correct). Increasing both A and T by 2 dB resulted in a combined A+T score increase of 10 percentage points (to 90.1 ±1.6 %-correct) over the greater of the single modality scores (i.e., A+2, 80%).

Two-way ANOVAs were performed on the arcsine-transformed percent-correct scores for each individual A, T, and combined A+T condition (all combinations of level). The results from the ANOVAs showed that scores on all A+T combined conditions were significantly greater than those of their single-modality counterparts. When the single-modality stimuli were equal in sensation level (both A and T presented at 0 dB SL or both A and T presented at 2 dB SL), their scores were not significantly different from one another. However, when the single-modality stimuli were different in level (one was 0 dB

SL and the other one was 2 dB SL), the single-modality responses were significantly different from one another (i.e., the modality presented at 2 dB SL always had significantly higher scores than those of the modality at 0 db SL). No significant effects of Subject were observed for any condition, and no significant interaction effects of Condition and Subject were observed for any condition.

A second two-way ANOVA was performed on all four A+T conditions and showed no significant effect for Condition [F(3,61) = 1.52, p = 0.2181], a significant effect for Subject [F(4,61) = 6.12, p < 0.0003], and no effect for their interaction. A *post hoc* Tukey-Kramer analysis showed that scores for subjects S_6 and S_{10} were significantly greater than those for subjects S_{18}, S_{23}, and S_{24}.

An analysis of the data in terms of three predictive models of integration, the Optimal Single Channel Model (OSCM), the Pythagorean Sum Model (PSM) and the Algebraic Sum Model (ASM), was performed on all of the combined A+T results. Table 5.1 summarizes the results of the Chi-Squared analysis of the observations versus predictions. The results suggest that the Baseline and the A+(T+2dB) conditions are best modeled by the ASM (82% and 63% of observations fitting predictions, respectively). The (A+2dB)+T condition was best fit by the PSM while the responses from the (A+2dB)+(T+2dB) condition were predicted equally well by all three models (58% of observations fitting predictions for all three models). As in previous results, however, the number of model over-predictions was higher for OSCM and PSM than for the ASM case.

Two-way ANOVAs were performed on each of the combined A+T conditions and their respective model predictions. The ANOVAs showed that when the auditory stimulus was presented at 0 dB SL, the combined A+T response was always significantly greater than the PSM and not significantly different from the ASM prediction, regardless of the relative level of the T stimulus (A+T and PSM: [F(1,34) = 16.46, p = 0.0003]; A+T and ASM [F(1,34) = 0.2, p = 0.6568]. A+(T+2dB) and PSM: [F(1,28) = 4.58, p = 0.0412]; and A+(T+2dB) and ASM [F(1,28) = 0.2, p = 0.655]). On the other hand, when the auditory stimulus was presented at 2 dB SL, the combined A+T responses were not significantly different from either the PSM or ASM predicted responses, regardless of the relative level of the tactile stimulus (A+2dB+T and PSM: [F(1,32)=0.87, p = 0.3588] and ASM: [F(1,32) = 3.73, p = 0.0624]; and A+2dB+T+2dB and PSM: [[F(1,28) = 2.47, p = 0.1274] and ASM: [F(1,28) = 1.8, p = 0.1907]). In all conditions, the combined A+T response was significantly greater than the response predicted by the OSCM.

IV. DISCUSSION

This experiment examined the effect of relative intensity in an auditory-tactile detection task. We found that the A+2 dB SL and T+2 dB SL measurements were significantly greater than their 0 dB SL counterparts (A-alone and T-alone, respectively) and that all combined A+T scores were significantly greater than the single-modality conditions. While we found no statistical difference between the four A+T %-correct scores, when compared with predictions from two different models a different view emerges. The PSM assumes that the two senses are integrated across separate channels (e.g., as in audio-visual integration, Braida, 1991), while the ASM assumes that the two senses are integrated within the same channel. ANOVAs showed that the %-correct scores on all four conditions were accounted for by the ASM, but only two conditions {(A+2)+T and (A+2)+(T+2)} were also accounted for by the PSM. Performance on the A+T and

A+(T+2) conditions was significantly greater than predicted by the PSM. These results suggest that the level of the auditory stimulus seems to be the dominant factor in determining which model best predicts the data, even though statistical tests showed that all four A+T results were not significantly different from one another.

Our results showing that the single-modality A+2 dB and the T+2dB were significantly greater than the A-alone and T-alone (at 0 dB SL levels) are consistent with previous psychometric data showing that a 1-dB increase in signal level above detection threshold results in a 5 percentage-point increase in performance. Similar results were observed for both auditory-alone and tactile-alone stimuli and suggest that both the auditory and tactile senses have similar shapes of the psychometric function.

The results have implications for testing auditory and tactile integration at levels that are above the threshold of detection, since the results in the combined A+T condition were not significantly different from one another. The observations of similar levels of response when both auditory and tactile are above threshold compared to when they are presented at threshold was somewhat unexpected and imply a ceiling effect on performance in the A+T condition as measured using the current methodology. We expected to see a 5 percentage-point increase in performance in the combined condition for every 1-dB increase above threshold in each single-modality (as we found in the A-alone and T-alone responses), implying that increasing the level of either or both the auditory or tactile stimulus would have significantly increased the response in the combined condition. Performance may have been limited, for example, by the subject's level of attention (i.e., less attention for more salient stimuli).

On the other hand, our results suggest that a measureable level of integration occurs at supra-threshold levels as well as at near-threshold levels (a result which was also observed in the Loudness Matching experiment when all stimuli were presented well above threshold) and makes the results more environmentally relevant (most stimuli in our daily lives are well above threshold). Additionally, finding significant integrative results at supra-threshold levels opens the possibility of performing neuroimaging studies on auditory-tactile integration at levels higher than threshold.

Table I. Results of the Chi-Squared tests for the different parameters and different models.

Condition	***Total***	***Optimal Single Channel***			***Pythagorean Sum***			***Algebraic Sum***		
		Pass	***Fail***	***Under predict Fail***	***Pass***	***Fail***	***Under predict Fail***	***Pass***	***Fail***	***Under predict Fail***
Intensity relative to threshold (SL)										
A=T=0dB	22	12 (55%)	10	10	17 (77%)	5	5	18 (82%)	4	2
A=2dB T= 0 dB	21	15 (71%)	6	6	16 (76%)	5	4	10 (48%)	11	2
A=0dB T=2dB	19	9 (47%)	10	9	19 (58%)	8	6	12 (63%)	7	3
A=T=2dB	19	11 (58%)	8	8	11 (58%)	8	6	11 (58%)	8	2

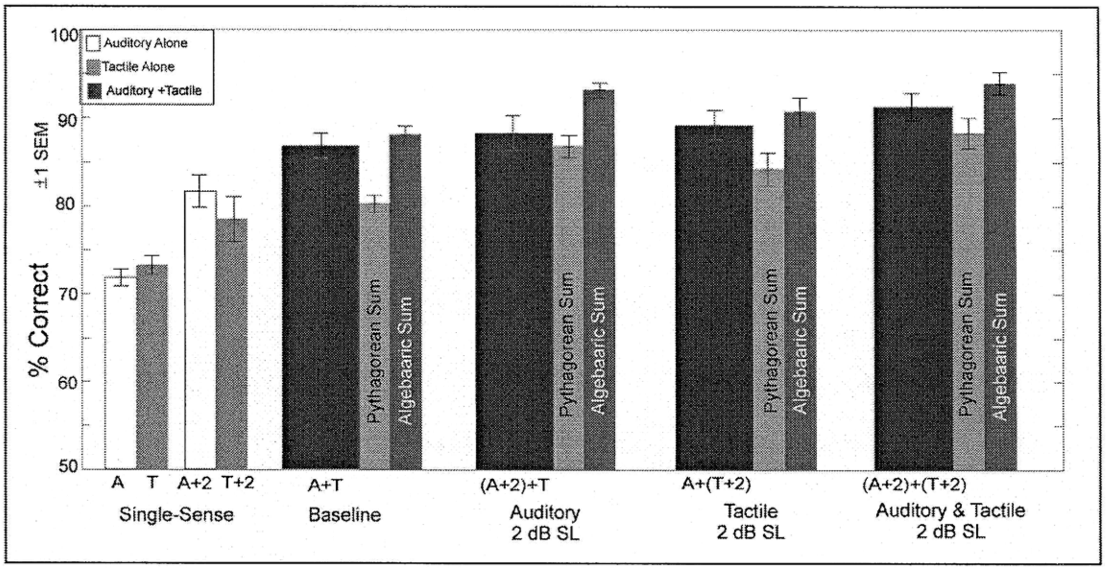

Figure 1: % correct averaged across 5 subjects with 4 sessions per condition, on average. The white bars represent the auditory alone scores and the light grey bars represent the tactile alone scores. The black bars represent the condition in which both auditory and tactile stimuli are presented together. Medium-grey bars represent the predictions of the PSM and dark-grey bars represent the predictions of the ASM. Error bars are one SEM.

Chapter 6. Summary and Future Work

The first set of experiments, detailed in Chapter 2: Effects of Phase and Temporal Synchrony, details the results of two main experiments. The first experiment studied the effect of relative auditory-tactile phase and our results indicated that performance increased significantly over unimodal detection when the auditory and tactile signals were presented synchronously, and that the combined performance increase was not affected by the relative phase between the auditory and tactile stimuli. The lack of a phase effect suggests an envelope rather than a fine-structure operation for integration. The second experiment studied the effect of relative temporal synchrony between the auditory and tactile stimuli and showed that responses were highest when the auditory and tactile stimuli were presented synchronously (i.e., same onset and offset), that responses were also high when the tactile signal precedes the auditory signal with up to 100 ms gaps between offset of tactile and onset of auditory, and that responses were roughly equivalent to single-modality levels when the auditory stimulus preceded the tactile stimulus for all gap durations. The effects of presenting the auditory and tactile stimuli with no temporal overlap (i.e., asynchronously) were consistent with time constants deduced from single-modality masking experiments. For example, when the tactile signal preceded the auditory signal, the significant increase in performance could be attributable to the neural persistence of the tactile stimulus even after the tactile stimulus had ceased, which has been found to be approximately 150 to 200 ms in tactile forward masking experiments. On the other hand, when the auditory stimulus was presented before the tactile stimulus (with no temporal overlap), the decreased performance could be attributable to the shorter auditory time constants (roughly 50 ms or less) found in auditory-only forward masking experiments.

The next set of experiments, detailed in Chapter 3: Effects of Frequency, presented the results of three complementary experiments. The first experiment studied the effect of varying the auditory frequency while holding the tactile frequency constant. The second experiment studied the effect of varying the tactile frequency while holding the auditory frequency constant. The third experiment studied the effect of equating the auditory and tactile frequencies and then co-varying them. The results of these three experiments indicate a significant increase in detectability over the single-modality cases when the auditory and tactile frequencies are within an octave of one another, and that absolute frequency does appear to matter, as detections in Experiment 3 at frequencies on the border of the Pacinian range (around 50 Hz) were not as high for some subjects as they were for others. Additionally, the Appendix of this chapter presented data from an experiment similar to Experiment 1, but with the tactile stimulus replaced by an auditory narrow band noise centered at 250 Hz. The results of this study are similar in shape to those found in Experiment 1, and suggest that when the auditory stimuli are close together in frequency, a greater level of signal detectability can be measured.

The next set of experiments, detailed in Chapter 4: Effects of Frequency at Supra-Threshold Levels, measured auditory-tactile interactions at levels that were well above threshold using a loudness matching experiment in which the frequencies of the auditory and tactile stimuli were the parameters being manipulated. The results show that the matched loudness of an auditory pure tone was greater when the frequencies of combined auditory and tactile stimuli were farther apart in frequency than when they were equal in frequency. These results are consistent with the results found in Chapter 3, exploring the frequency relationships at near-threshold levels, and shows that the frequency relationship found at low signal levels is also present at supra-threshold levels. The results are also consistent with results found in auditory-only literature concerning critical bands and suggest that the auditory and tactile systems are interacting in a manner similar to the interactions of purely auditory stimuli. Specifically, our results suggest that there may be 1) a critical band-like structure within the tactile Pacinian system and that 2) the auditory and tactile sensory systems may have a cross-modal tonotopic relationship that is present at both near-threshold and supra-threshold levels.

The last set of experiments, detailed in Chapter 5: Effects of Relative Intensity, explored how the auditory and tactile stimuli interacted with one another at multiple points along the psychometric curve. In these experiments, we studied auditory and tactile integration at 0 dB SL (near threshold) and at 2 dB SL (slightly above threshold). We showed that while the single-modality detection rates increased with increasing dB level, the responses to the combined A+T stimulus was relatively constant regardless of the relative intensity of the individual components. There was a difference in response when the combined results were compared with different models, however, such that all four combined A+T conditions were not significantly different from the ASM, but that only the conditions in which the auditory stimulus was presented at 0 dB SL [A+T and A+(T+2dB)] were significantly greater than the PSM. The results suggest that the auditory and tactile stimuli have similar psychometric shapes and that we may have reached a ceiling in effect when raising the signal level in a detection task.

Future Work

This thesis studied the integration of auditory and tactile stimuli in normal hearing adults. Future work in this area includes expanding the detection and loudness matching experiments to different populations of individuals, such as hearing impaired adults and cochlear implantees. Additionally, since it has been shown that some children with autism or dyslexia have sensory integration difficulties compared with typically developing children, designing a set of experiments to test their integration of auditory and tactile stimuli may shed some light on the nature of their sensory processing disorders. Our research in the frequency relationship between the auditory and tactile senses could also be expanded to test for multiple critical bands within the tactile Pacinian system. If such a frequency grouping is found, then it may be possible to measure the subjective phenomenon called "stream segregation" in the tactile sense. Results from this could be used to explore cross-modal stream segregation. Ultimately the research in this area could be utilized to create assistive tactile devices that would deliver information regarding the auditory cues, such as speech, that are prevalent in an individual's environment.

Additionally, future work in this area includes neuroimaging studies of auditory-tactile integration. Given that the loudness matching experiment (Chapter 4) showed a measureable frequency relationship between the auditory and tactile stimuli at supra-threshold levels, utilizing functional magnetic resonance imaging (fMRI) to study the temporal and anatomical interactions between these two sensory systems would be feasible, as such experiments are performed at supra-threshold signal levels. Our perceptual experiments have suggested a cross-modal tonotopic relationship between the auditory and tactile senses, and imaging methodologies, such as fMRI and diffusion tensor imaging (DTI) might be successful in quantifying this relationship in the central nervous system.

BIBLIOGRAPHY

Bensmaia, S. J., Hollins, M., and Yau J. **(2005).** "Vibrotactile intensity and frequency information in the Pacinian system," Percept. Psychophys. **67**, 828-841.

Bhattacharya, J., Shams, L., and Shimojo, S. **(2002).** "Sound-induced illusory flash perception: Role of gamma band responses," NeuroReport 13, 1727-1730.

Bilecen, D., Scheffler, K., Schmid, N., Tschopp, K., Seelig, J. (**1998**). "Tonotopic organization of the human auditory cortex as detected by BOLD-FMRI." Hear. Res., **126,** 19-27.

Bolanowski, S.J., Gescheider, G.A., Verrillo, R.T., (**1988**). "Four channels mediate the mechanical aspects of touch." J. Acoust. Soc. Am., **84**, 1680-1694.

Braida, L. D. **(1991).** "Crossmodal integration in the identification of consonant Segments," Q. J. Exp. Psychol., **43A,** 647-677.

Bresciani, J. P., Ernst, M. O., Drewing, K., Bouyer, G., Maury, V., and Kheddar, A. **(2005).** "Feeling what you hear: auditory signals can modulate tactile tap perception," Exp. Brain. Res. **162,** 172-180.

Caclin, A., Soto-Faraco, S., Kingstone, A., and Spence, C. **(2002).** "Tactile "capture" of audition," *Percept. Psychophys*. **64**, 616-630.

Caetano, G. and Jousmaki, V. **(2005).** “Evidence of vibrotactile input to human auditory cortex,” Neuroimage. **29**, 15-28.

Cappe, C. and Barone, P. **(2005).** “Heteromodal connections supporting multisensory integration at low levels of cortical processing in the monkey,” Eur. J. Neurosci.. **22.** 2886-2902.

Craig, J. C. and Evans, P. M. **(1987).** “Vibrotactile masking and the persistence of tactual features,” Percept. Psychophys. **42**, 309-317.

Dadson, R.S., and King, J.H., (**1952**). “A determination of the normal threshold of hearing and its relation to the standardization of audiometers.” J. Laryng. Otol.. **66**, 366-378

Dirks, D. D., Kamm, C., and Gilman, S. **(1976)**. “Bone-conduction thresholds for normal listeners in force and acceleration units,” J. Speech Hear. Res., **19**, 181-186.

Ernst, M. O. and Banks, M. S. **(2002).** “Humans integrate visual and haptic information in a statistically optimal fashion,” Nature. Jan 24; **415,** 429-33.

Fastl, H. **(1977).** “Subjective duration and temporal masking patterns of broadband noise impulses,” J. Acoust. Soc. Am. **61**, 62-168.

Fletcher, H., (**1940**). “Auditory Patterns.” Revs. Mod. Physics, **12**, 47-65.

Fletcher, H., and Wegel, R.L., (**1922).** “The frequency-sensitivity of normal ears.” Proceedings of the National Academy of Sciences, **8**, 5-8.

Formby, C., Morgan, L. N., Forrest, T., G., Raney, J. J. (**1992**). “The role of frequency selectivity in measures of auditory and vibrotactile temporal resolution.” J. Acoust. Soc. Am., **91**, 293-305.

Foxe, J. J., Wylie, G. R., Martinez, A., Schroeder, C. E., Javitt, D. C., Guilfoyle, D., Ritter, W., and Murray, M. M. **(2002).** “Auditory-somatosensory multisensory processing in auditory association cortex: an fMRI study,” J. Neurophys. **8,** 540-543.

Francis, S. T., Kelly, E. F., Bowtell, R., Dunseath, W. J. R., Foger, S. E., McGlone, F. (**2000**). “fMRI of the responses to vibratory stimulation of digit tips.” NeuroImage, **11**, 188-202.

Fritzsch, B., and Beisel, K W. (**2001**). “Evolution of the nervous system.” Brain Res. Bull., **55** (6), 711-721.

Fritzsch, B., Beisel, K. W., Pauley, S., Soukup, G. (**2007**). “Molecular evolution of the vertebrate mechanosensory cell and ear.” Int. J. Dev. Biol., **51**, 663-678.

Fu, K. M. G., Johnston, T. A., Shah, A. S., Arnold, L., Smiley, J., Hackett, T. A., Garraghty, P. E., and Schroeder, C. E. **(2003).** "Auditory cortical neurons respond to somatosensory stimulation," J. Neurosci. **23**, 7510-7515.

Gescheider, G. A., Barton, W. G., Bruce, M. R., Goldberg, J. H., and Greenspan, M. J. **(1969).** "Effects of simultaneous auditory stimulation on the detection of tactile stimuli," J. Exp. Psych. **81**, 120-125.

Gescheider, G.A., Bolanowski, S.J., Hardick, K.R., (**2001**). "The frequency selectivity of information-processing channels in the tactile sensory system." Somato. Motor Res., **18**, 191-201.

Gescheider, G.A., Bolanowski, S.J., Pope, J.V., Verrillo, R.T., (**2002**). "A four-channel analysis of the tactile sensitivity of the fingertip: frequency selectivity, spatial summation, and temporal summation." Somato. Motor Res., **19**, 114-124.

Gescheider, G. A., Bolanowski, S. J., and Verrillo, R. T. **(1989)**. "Vibrotactile masking: effects of stimulus onset asynchrony and stimulus frequency," J. Acoust. Soc. Am. **85**, 2059-2064.

Gescheider, G. A., Hoffman, K. E., Harrison, M. A., and Travis, M. L. **(1994).** "The effects of masking on vibrotactile temporal summation in the detection of sinusoidal and noise signals," J. Acoust. Soc. Am.. **95**, 1006-1016.

Gescheider, G. A., Kane, M. J., and Sager, L. C. **(1974).** "The effect of auditory stimulation on responses to tactile stimuli," Bull. Psychon. Soc. **3**, 204-206.

Gescheider, G. A. and Migel, N. **(1995).** "Some temporal parameters in vibrotactile forward masking," J. Acoust. Soc. Am. **98**, 3195-3199.

Gescheider, G. A. and Niblette, R. K. **(1967).** "Cross-modalidty masking for touch and hearing," J. Exp. Psych. **74**, 313-320.

Gescheider GA, Thorpe JM, Goodarz J, Bolanowski SJ **(1997)**. The effects of skin temperature on the detection and discrimination of tactile stimulation. *Somatosensory & Motor Research.* 14(3):181-188

Gillmeister, H. and Eimer, M. **(2007).** "Tactile enhancement of auditory detection and perceived loudness," Brain Res. **1160**, 58-68.

Gray, H., Bannister, L. H., Berry, M. M., Williams, P. L. **(1995)** Gray's Anatomy, 38th edition. Churchill Livingstone Publishers.

Green, D. M. **(1958).** "Detection of multiple component signals in noise," J. Acoust. Soc. Am. **30,** 904-911.

Guest, S., Catmur, C., Lloyd, D., and Spence, C. **(2002).** "Audiotactile interactions in roughness perception," Exp Brain Res. **146,** 161-171.

Hackett, T. A., de la Mothe, L. A., Ulbert, I., Karmos, G., Smiley, J., and Schroeder, C. E. **(2007). "**Multisensory convergence in auditory cortex, II. Thalamocortical connections of the caudal superior temporal plane," J. Comp. Neurol. **502,** 924-952.

Hamer, R. D., Verrillo, R. T., and Zwislocki, J. J. **(1983).** "Vibrotactile masking of pacinian and non-pacinian channels," J. Acoust. Soc. Am. **73**,1293-1303.

Harrington, G. S., and Downs, J. H., III (**2001**). "FMRI mapping of the somatosensory cortex with vibratory stimuli. Is there a dependency on stimulus frequency?" Brain Res., **897**, 188-192.

Harris, J. A., Arabzadeh, E., Fairhall, A. L., Benito, C., Diamond, M. E. (**2006**). "Factors affecting frequency discrimination of vibrotactile stimuli: Implications for cortical encoding." Pub. Lib. Sci., **1**, 1-9.

Hashimoto, I., Saito, Y., Iguchi, Y., Kimura, T., Fukushima, T., Terasaki, O., Sakuma, K. (**1999**). "Frequency representation in the human hand somatosensory cortex: a reappraisal." NeuroReport, **10**, 959-963.

Hawkins, J. E. and Stevens, S.S. **(1950).** “The masking of pure tones and of speech by white noise,” J. Acoust. Soc. Am. **22**, 6-13.

Hegner, Y. L., Saur, R., Veit, R., Butts, R., Leiberg, S, Grodd, W., Braun, C. **(2007)**. “BOLD adaptation in vibrotactile stimulation: Neuronal networks involved in frequency discrimination.” J. Neurophysiol., **97**, 264-271.

Hernandez, A., Zainos, A., Romo, R. (**2000**). “Neuronal correlates of sensory discrimination in the somatosensory cortex.” Proc. Nat. Acad. Sci., **97**, 6191-6196.

Houtsma, A. J. **(2003). “**Hawkins and Stevens revisited with insert earphones,” J. Acoust. Soc. Am., **115**, 967-970.

Iguchi, Y., Hoshi, Y., Nemoto, M., Taira, M., Hashimoto, I. (**2007**). “Co-activation of the secondary somatosensory and auditory cortices facilitates frequency discrimination of vibrotactile stimuli.” Neurosci., **148**, 461-472.

Jesteadt, W. (**1980**). “An adaptive procedure for subjective judgements.” Percep. Psychophys., **28**, 85-88.

Jesteadt, W., Bacon, S. P., and Lehman, J. R. **(1982).** “Forward masking as a function of frequency, masker level, and signal delay,” J. Acoust. Soc. Am., **71**, 950 – 962.

Jousmaki, V. and Hari, R. **(1998).** “Parchment-skin illusion: sound-biased touch,” Curr. Biol., **8,** R190.

Kayser, C., Petkov, C. I., Augath, M., and Logothetis, N. K. **(2005)**. “Integration of touch and sound in auditory cortex,” Neuron. **48**, 373-384.

Kidd, G., Jr. and Feth, L. L. **(1981)**. “Patterns of residual masking,” Hear. Res. **5,** 49-67

Lafuente, V. de., and Romo, R. (**2005**). “Neuronal correlates of subjective sensory experience.” Nature Neurosci., **8**, 1698-1703.

Lakatos, P., Chen, C. M., O’Connell, M. N., Mills, A., and Schroeder, C. E. **(2007)**. “Neuronal oscillations and multisensory interaction in primary auditory cortex,” Neuron. **53**, 279-292.

Lamore P. J., Muijser, H., and Keemijik, C. J. **(1986)**. “Envelope detection of amplitude-modulated high-frequency sinusoidal signals by skin mechanoreceptors,” J. Acoust. Soc. Am. **79,** 1082-1085.

Leibold, L. J., and Jesteadt, W. (**2007**). “Use of perceptual weights to test a model of loudness summation.” JASA Express Letters, 21 Aug.

Leibold, L. J., Tan, H., Khaddam, S., and Jesteadt, W. (2007). “Contributions of individual components to the overall loudness of a multi-tone complex,” J. Acoust. Soc.

Am. 121, 2822–2831.

Levitt, H. **(1971).** “Transformed up-down methods in psychoacoustics,” J. Acoust. Soc. Am. **49**, 467-477.

Luna, R. Hernandez, A., Brody, C. D., Romo, R. (**2005**). “Neural codes for perceptual discrimination in primary somatosensory cortex.” Nature Neurosci., **8**, 1210-1219.

Markous, J. C., Friedman, R. M., Vierck, C. J., Jr. (**1995**). “A critical band filter in touch.” J. Neurosci., **15**, 2808-2818.

Marks, L. E. (**1979**). “Summation of vibrotactile intensity: An analog to auditory critical bands?” Sens. Proc. **3**, 188-203.

Marrill, T. **(1956). “**Detection theory and psychophysics.” Technical Report No. 319. Research Laboratory of Electronics, MIT, Cambridge, Massachusetts.

McGurk, H., and MacDonald, J. **(1976).** "Hearing lips and seeing voices," Nature **264**, 746-748.

Moore, B. C. J. and Glasberg, B. R. **(1983).** “Growth of forward masking for sinusoidal and noise maskers as a function of signal delay; implications for suppression in noise,” J. Acoust. Soc. Am. **73,** 1249-1259.

Moore, B. C. J., Glasberg, B. R., Plack, C. J., and Biswas, A. K. **(1988).** "The shape of the ear's temporal window," J. Acoust. Soc. Am. **83**, 1102-1116.

Moore, B. C., J., Peters, R. W., Glasberg, B. R. (**1990**). "Auditory filter shapes at low center frequencies." J. Acoust. Soc. Am. **88**, 132-140.

Morley, J. W. and Rowe, M. J. (**1990**). "Perceived pitch of vibrotactile stimuli: Effects of vibration amplitude, and implications for vibration frequency coding." J. Physiol. **431**, 403-416.

Neville, A. M., and Kennedy, J. B. **(1964).** *Basic statistical methods for engineers and scientists* (International Textbook Co, Scranton, PA), p. 133.

O'Connell-Rodwell, C. E., Hart, L. A., Arnason, B. T,(**2001**). "Exploring the potential use of seismic waves as a communication channel by elephants and other large mammals." Amer. Zool. **41**, 1157-1170.

Plack, C. J. and Oxenham, A. J. **(1997).** "Basilar-membrane nonlinearity and the growth of forward masking," J. Acoust. Soc. Am. **103**, 1598-1608.

Rabinowitz, W. M., Houtsma, A. J., Durlach, N. I., and Delhorne, L. A. **(1987).** "Multidimensional tactile displays: Identification of vibratory intensity, frequency and contactor area," J. Acoust. Soc. Am. **82**, 1243 – 1252.

Ro, T., Hsu, J., Yasar, N. E., Elmore, L. C., and Beauchamp, M. S. **(2009).** "Sound enhances touch perception," Exp. Brain Res. **195**, 135-143.

Robinson, C. E. and Pollack, I. **(1973).** "Interaction between forward and backward masking: a measure of the integrating period of the auditory system," J. Acoust. Soc. Am. **53,** 1313-1316.

Romani, G. L., Williamson, S., J., Kaufman, L., (**1981**). "Tonotopic organization of the human auditory cortex." Science, **216**, 1339-1340.

Romo, R., Hernandez, A., Zainos, A., Brody, C. D., Lemus, L. (**2000**). "Sensing without touching: Psychophysical performance based on cortical microstimulation." Neuron, **26**, 273-278.

Romo, R., Hernandez, A., Zainos, A., Salinas, E. (**1998**). "Somatosensory discrimination based on cortical microstimulation." Nature, **392**, 387-390.

Schnupp, J. W. H., Dawe, K. L., and Pollack, G. **(2005).** "The detection of multisensory stimuli in an orthogonal sensory space," Exp Brain Res. **162,** 181-190.

Schnupp, J. W. H. **(2009).** Personal communication to L.D. Braida.

Schreiner, C.E., Read, H.L., Sutter, M.L., (**2000**). "Modular organization of frequency integration in primary auditory cortex." Annu. Rev. Neurosci., **23**, 501-529.

Schroeder, C. E., Lindskey, R. W., Specht, C., Marcovici, A., Smiley, J. F., and Javitt, D. C. **(2001).** "Somatosensory input to auditory association cortex in the macaque monkey," *J. Neurophys.* **85,** 1322-7.

Schurmann, M., Caetano, G., Jousmaki, V., and Hari, R. (**2004**). "Hands help hearing: Facilitatory audiotactile interaction at low sound-intensity levels," J. Acoust. Soc. Am. **115**, 830-832.

Schurmann, M., Caetano, G., Hlushchuk, Y., Jousmaki, V., and Hari, R. **(2006).** "Touch activates human auditory cortex," Neuroimage. **30,** 1325-1331.

Sekuler, R., Sekuler, A. B., and Lau, R. **(1997).** "Sound alters visual motion perception," Nature **385**, 308.

Shore, S. and Zhou, J. **(2006)**. Somatosensory influence on the cochlear nucleus and beyond. *Hearing Research*. 216-217. pp. 90-99.

Silva, I., Florentine, M. (**2006**). "Effect of adaptive psychophysical procedure on loudness matches." J. Acoust. Soc. Am., **120**, 2124-2131.

Smiley, J. F., Hackett, T. A., Ulbert, I., Karmas, G., Lakatos, P., Javitt, D. C., and Schroeder, C. E. **(2007).** "Multisensory convergence in auditory cortex, I. Cortical connections of the caudal superior temporal plane in macaque monkeys," J. *Comp. Neurol.* **502**, 894-923.

Soto-Faraco, S., Spence, C., and Kingstone, A. **(2004)**. "Congruency effects between auditory and tactile motion: Extending the phenomenon of cross-modal dynamic capture," Cogn. Affect. Behav. Neurosci. **4**, 208-217.

Stein, B. E., London, N., Wilkinson, L. K., and Price, D. D. **(1996).** "Enhancement of perceived visual intensity by auditory stimuli: a psychophysical analysis," J. Cog. Neurosci. **8**, 497-506.

Stein, B. E. and Meredith, M. A. **(1993).** *The Merging of the Senses* (MIT Press, Cambridge, MA).

Squire, L. R., Roberts, J. L., Spitzer, N. C., Zigmond, M. J., McConnell, S. K., Bloom, F. E. (2002). Fundamental Neuroscience, Second Edition. Academic Press, Elsevier Science, San Diego, CA.

Swets, J. A., Green, D. M., Tanner, W. P., Jr. (**1962**). "On the width of critical bands." J. Acoust. Soc. Am. **22**, 108-113.

Talavage, T. M., Ledden, P. J., Benson, R. R., Rosen, B. R., Melcher, J. R. (**2000**). "Frequency-dependent responses exhibited by multiple regions in human auditory cortex." Hear. Res., **150**, 225-244.

Talavage, T. M., Sereno, M. I., Melcher, J. R., Ledden, P. J., Rosen, B. R., Dale, A. M. (**2004**). "Tonotopic organization in human auditory cortex revealed by progressions of frequency sensitivity." J. Neurophysiol., **91**, 1282-1296.

Verrillo, R.T., **(1963).** "Effect of contactor area on the vibrotactile threshold." J. Acoust. Soc. Am., **35**, 1962-1966.

Verillo, R. T., Gescheider, G. A., Calman, B. G. and Van Doren, C. L. **(1983).** "Vibrotactile masking: Effect of one- and two-site stimulation," Percept. Psychophys., **33**, 379-387.

Vogten, L. L. M. **(1977).** "Simultaneous pure-tone masking: The dependence of masking asymmetries on intensity," J. Acoust. Soc. Am. **63,** 1509-1519.

Watson, C.S., Franks, J.R., and Hood, D.C., (**1972**). "Detection of tones in the absence of external noise I. Effects of signal intensity and signal frequency." J. Acoust. Soc. Am. **52,** 633-643.

Weitz, J. **(1941).** Vibratory Sensitivity as a Function of Skin Temperature. *Journal of Experimental Psychology* 28, p. 21-36

Wilson, E.C., Reed, C.M., Braida, L.D., (**2009**). “Integration of auditory and vibrotactile stimuli: Effects of phase and stimulus-onset asynchrony.” J. Acoust. Soc. Am., **126**, 1960-1974.

Wilson, E. C., Reed, C. M., and Braida, L. D. **(under review).** “Integration of auditory and vibrotactile stimuli: Effects of frequency.” J. Acoust. Soc. Am.

Woods, T. M. and Recanzone, G. H. **(2004).** "Cross-modal interactions evidenced by the ventriloquism effect in humans and monkeys," In G. Calvert, C. Spence, and B.E. Stein (Eds.), Handbook of Multisensory Processes (pp.35-48). MIT Press, Cambridge, MA.

Yarrow, K., Haggard, P., and Rothwell, J. C. **(2008).** “Vibrotactile-auditory interactions are post-perceptual,” Perception, **37**, 1114-1130.

Yau, J.M., Olenczak, J.B., Dammann, J.F., Bensmaia, S.J., (**2009**). “Temporal frequency channels are link across auditory and touch.” Curr. Biol., **19**

Zhou, J. and Shore, S. **(2004).** “Projections from the trigeminal nuclear complex to the cochlear nuclei:A retrograde and anterograde tracing study in the guinea pig,” *J. Neurosci. Res.* **78,** 901-907.

Zwicker, E. (**1961**). “Subdivision of the audible frequency range into critical bands (frequenzgruppen).” J. Acoust. Soc. Am., **33**, 248.

Zwicker, E., Flottorp, G., Stevens, S. (**1957**). “Critial Band Width in Loudness Summation.” J. Acoust. Soc. Am., **29**, 548-557.